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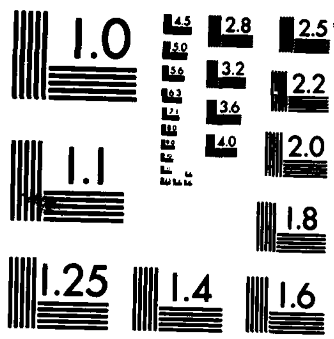

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Atlas of Northern Hemisphere Density Between 30 and 60 km

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29 SEPTEMBER 1982

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AIR FORCE SYSTEMS COMMAND, USAF

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

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Alva T Stair, Jr.

DR. ALVA T. STAIR, Jr
Chief Scientist

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Mean seasonal density charts for the Northern hemisphere for 5-km increments of altitude between 30 and 60 km are presented in this report, along with estimates of the day-to-day variations around the mean seasonal values. This meets the need for a climatology of atmospheric density at constant altitudes above radiosonde levels. These charts are based on compilations of data by workers at the National Meteorological Center, NOAA, who combined data from TIROS operational vertical sounders with

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20. Abstract (Continued)

meteorological rocketsonde observations to produce once-weekly analyses of height and temperature fields for the Northern hemisphere at the 5, 2, 1, and 0.4 mb levels for the period July 1976 through April 1980.

Preface

The author acknowledges Mr. R. Raistrick and A1C N. Bonito for their efforts in computerizing the many statistical and other mathematical procedures required to provide the end product of this research. Thanks are also proffered to Mr. E. A. Bertoni for his work in preparing the density maps for reproduction. *Finally, the author thanks Mrs. Helen Connell* for her patience as well as for her usual excellent preparation of the manuscript for publication.

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1. INTRODUCTION

The horizontal and vertical distribution of atmospheric density can be a significant factor in the design and operation of aerospace systems. Potential problems related to reentry trajectories and fuzing are particularly important, and a detailed knowledge of atmospheric density is required to evaluate vehicle performance. Variations in the distribution of density affect predicted deceleration and range of free-fall bombs and ballistic missiles that have high forward velocities. Consequently, engineers and designers of aerospace systems must consider vertical structure and day-to-day density variability as well as geographic and seasonal differences up to altitudes of at least 55 km. Diurnal variations are not addressed in this report.

Currently available density data at altitudes above radiosonde levels (30 km) are limited to densities derived from Meteorological Rocket Network observations at some 24 locations, mostly in the Northern Hemisphere. Height and temperature measurements from these rocketsondes and from TIROS satellite vertical sounders have been combined by the National Meteorological Center of the National Oceanic and Atmospheric Administration (NOAA) to produce hemispheric analyses of height and temperature fields at 5-, 2-, 1-, and 0.4-mb pressure surfaces (≈ 35 to 55 km).

(Received for publication 29 September 1982)

For maximum utility, however, information is needed at constant altitudes rather than along pressure surfaces. Therefore, we have used these data to derive hemispheric maps of mean seasonal density for spring (Mar, Apr, May); summer (Jun, Jul, Aug); fall (Sep, Oct, Nov); and winter (Dec, Jan, Feb) at 5-km altitude intervals from 30 through 55 km. We also present estimated day-to-day variations, or root-mean-square (rms) deviations around the mean seasonal values. The development of these maps is outlined in this report, which represents only one portion of a continuing effort to analyze and present information on the distribution of the thermodynamic properties of the atmosphere in forms most suitable for use in the design and operation of aerospace systems.

2. DATA

From 1964 through 1968, the National Meteorological Center has produced once-weekly charts of heights and temperatures over much of the northern hemisphere (centered on North and Central America) for pressure levels 5, 2, and 0.4 mb.[1-5] Meteorological Rocket Network data were essentially the only input during those five years. By 1972, data from experimental satellite temperature sounders became available; these data were used in conjunction with the Meteorological Rocket Network observations, so that height and temperature charts were extended to cover the entire northern hemisphere.[6-8] In July 1976, analyses of the height and temperature fields were expanded to include charts at the 1-mb pressure level. Objective analysis techniques have been employed since that time,

1. Staff, Upper Air Branch (1967) Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for 1964, ESSA Technical Report WB-2, Silver Spring, Md.
2. Staff, Upper Air Branch (1967) Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for 1965, ESSA Technical Report WB-3, Silver Spring, Md.
3. Staff, Upper Air Branch (1969) Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for 1966, ESSA Technical Report WB-9, Hillcrest Heights, Md.
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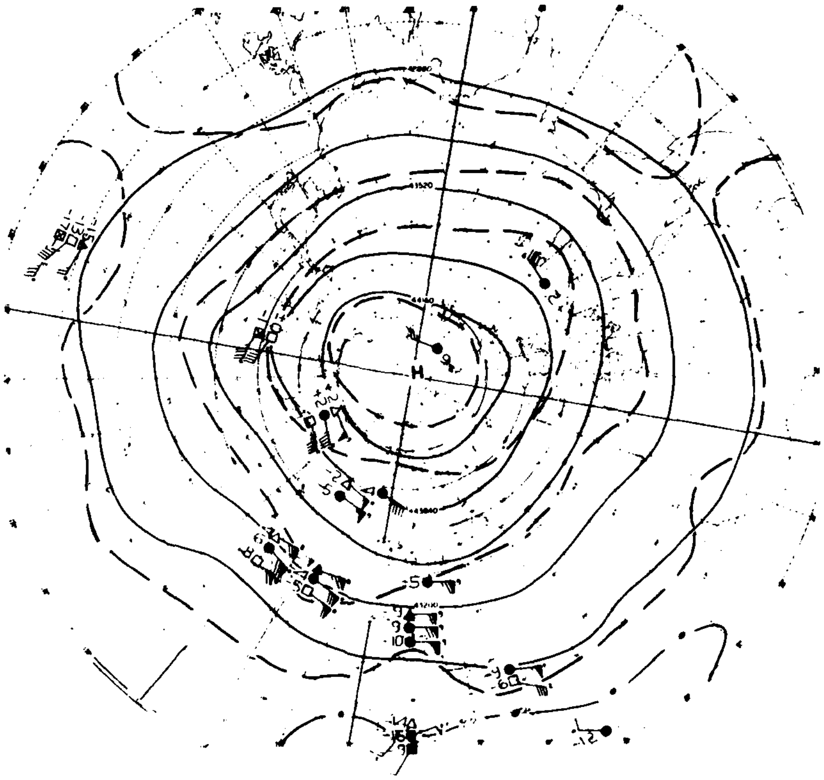
6. Staff, Upper Air Branch (1975) Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for January 1972 Through June 1973, NASA SP-3091, Camp Springs, Md.
7. Staff, Upper Air Branch (1976) Synoptic Analyses, 5-, 2-, and 0.4-mb Surfaces for July 1973 Through June 1974, NASA SP-3102, Camp Springs, Md.
8. Staff, Upper Air Branch (1978) Synoptic Analysis, 5-, 2-, and 0.4-mb Surfaces for July 1974 Through June 1976, NASA Reference Publication 1023, Camp Springs, Md.

producing hemispheric charts based on computer-determined grid-point values.[9] An example of such height and temperature analyses is shown in Figure 1 for the 2-mb level on 15 June 1977.



2-MB HEIGHTS AND TEMPERATURES, 15 JUNE 1977

Figure 1. Heights and Temperatures of the 2-mb Surface, 15 June 1977

The data that were used for this report consist of tapes of the National Meteorological Center grid-point values; they represent 200 once-weekly, 5-, 2-, 1-, and 0.4-mb height and temperature charts for 46 months from July 1976 through April 1980. The original fields consist of a 4225-point grid in a 65 × 65 array, with a grid increment of 381 km covering the entire northern hemisphere.

9. Gelman, M.E., Nagatani, R.M., Miller, A.J., Laver, J.D., and Finger, F.G. (1981) An evaluation of stratospheric meteorological analyses using satellite sounder and rocketsonde data, Handbook for MAP, Volume 2, SCOSTEP Secretariat, Univ. of Ill., Urbana, Ill., pp 1-9.

3. PROCEDURE

To determine monthly and seasonal densities at constant heights from once-weekly heights and temperature on constant pressure surfaces, several conversions, and mathematical and statistical procedures are required. First, all grid-point heights and temperatures were used to derive grid-point densities from the perfect gas law[10]

$$\rho = \frac{M\ P}{R^{*}\ T} \quad , \tag{1}$$

where ρ is atmospheric density in kg/m^3; M is the mean molecular weight of air, 28.9644 kg/kmol, considered constant up to approximately 80 km; P is atmospheric pressure in N/m^2; R^* is the universal gas constant, 8.31432×10^3 N m/kmol K; and T is atmospheric temperature in K. Because this sample is limited to only 46 months of once-weekly observations, computed densities were combined by season to provide more stable averages. In this manner, spring, summer, fall, and winter seasons each consist of 47 to 52 values rather than only 13 to 18 for each month.

3.1 Mean Densities

The distributions of density with altitude can be represented as relatively smooth vertical profiles when expressed as percent departure from the 1976 U.S. Standard Atmosphere.[10] Examples of such profiles are shown in Figure 2 which portrays vertical density structure in January and July at 30° and 45°N.[11] Data that produce profiles such as these readily lend themselves to curve-fitting and smoothing techniques. As a consequence, grid-point densities were averaged for each grid point at 5, 2, 1, and 0.4 mb and converted to percent departures from the Standard Atmosphere, at the mean heights of these pressure surfaces for each season. Third degree polynomial fits to these average values were then applied to provide mean seasonal density profiles at each grid point for altitudes corresponding to 5 mb through 0.4 mb.

At this juncture it should be noted that, since both density and pressure decrease nonlinearly with altitude, mean densities on a given pressure surface do not necessarily occur at exactly the mean height of that pressure surface. In reality, densities occur at a slightly lower altitude than that calculated from, and

10. COESA (1976) U.S. Standard Atmosphere, 1976, Superintendent of Documents, Washington, D.C.

11. COESA (1966) U.S. Standard Atmosphere Supplements, 1966, Superintendent of Documents, Washington, D.C.

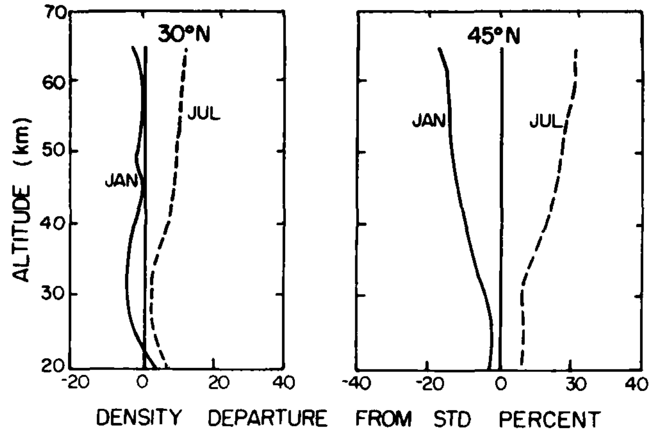


Figure 2. Density-altitude Profiles From the Standard Atmosphere Supplements, 1966

applied to the average altitude of, constant pressure surfaces. However, the accuracy of results appears more than adequate for the purposes of this report. Examples of the equations and polynomial fits to the mean seasonal densities are shown in Figures 3, 4 and 5 for grid points located one column or 381 km east of 80°W longitude at locations near 30°N (Figure 3), near 45°N (Figure 4), and near 60°N (Figure 5). As can be seen on the figures, third degree polynomial fits to four data points produce curves that go through every point. These are preferable to quadratic fits in which curvatures are unchanging and, therefore, represent unrealistic portrayals of vertical density profiles at these altitudes. The observational errors in densities derived from rocketsonde temperature measurements result in rms density errors that vary approximately linearly from 3 percent at 30 km to 5 percent at 65 km.[12]

As shown for the examples in Figures 3, 4 and 5, the altitude of the lowest data point, the 5-mb density, lies at or near 35 km. As a result, the curves were extrapolated downward roughly 5 km to provide meaningful estimates of the average density at 30 km. Because the polynomial fits become less realistic with distance beyond the data, the curves were extended downward linearly, as shown by the dashed lines, at the same slope as that at 5 mb (the lowest point of observation). Similar extensions upward (for shorter increments) to 55 km were made at those locations and seasons for which 0.4-mb densities were below 55 km. Examples of these extrapolated extensions are denoted by the upper dashed lines in Figures 3, 4, and 5.

12. Range Commanders Council (1981) Meteorological Data Error Estimates, Document 110-81, White Sands Missile Range, N.M.

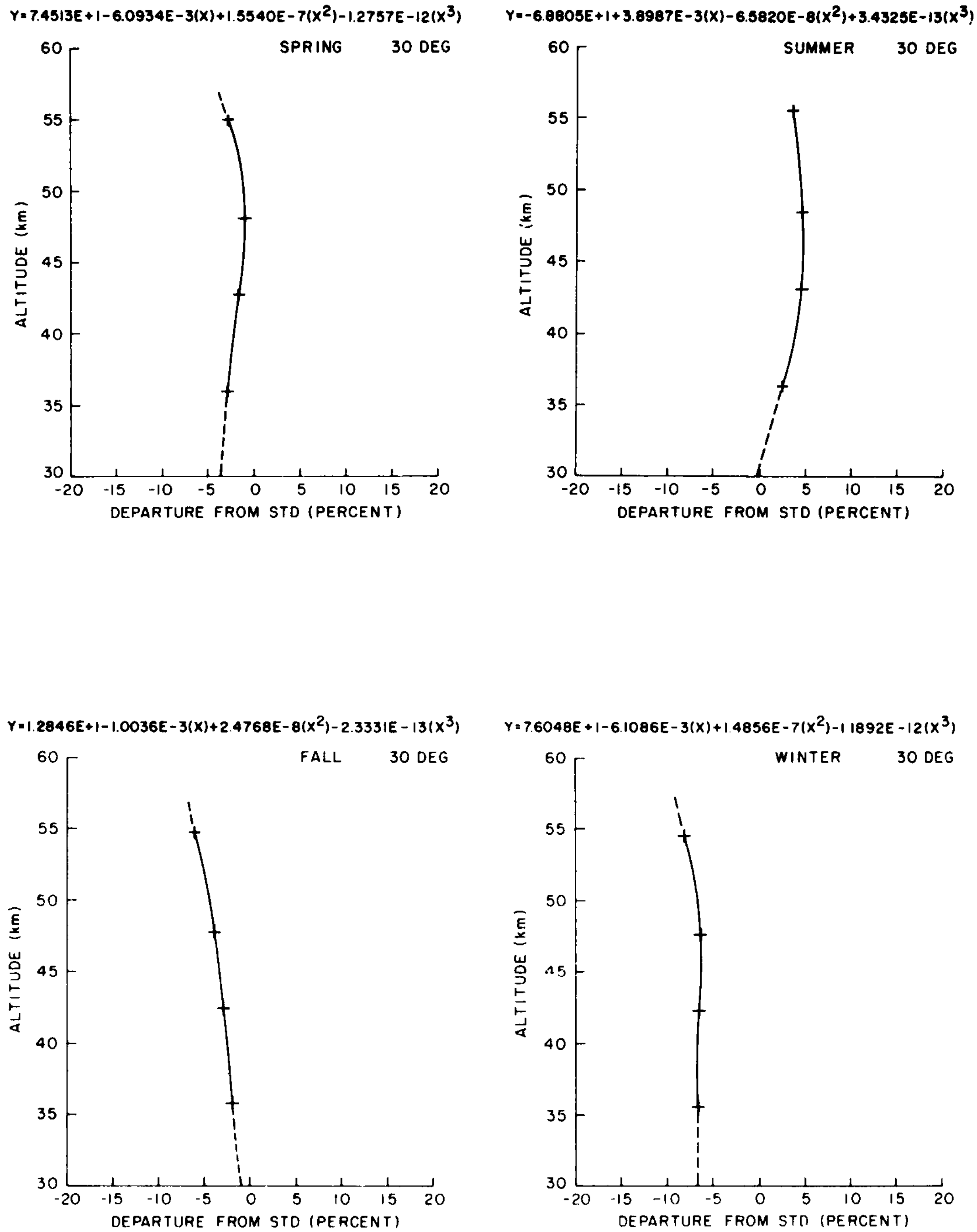


Figure 3. Third Degree Polynomial Fits to Mean Seasonal Densities for 5, 2, 1 and 0.4-mb Pressure Surfaces at a Grid-point Near 30°N

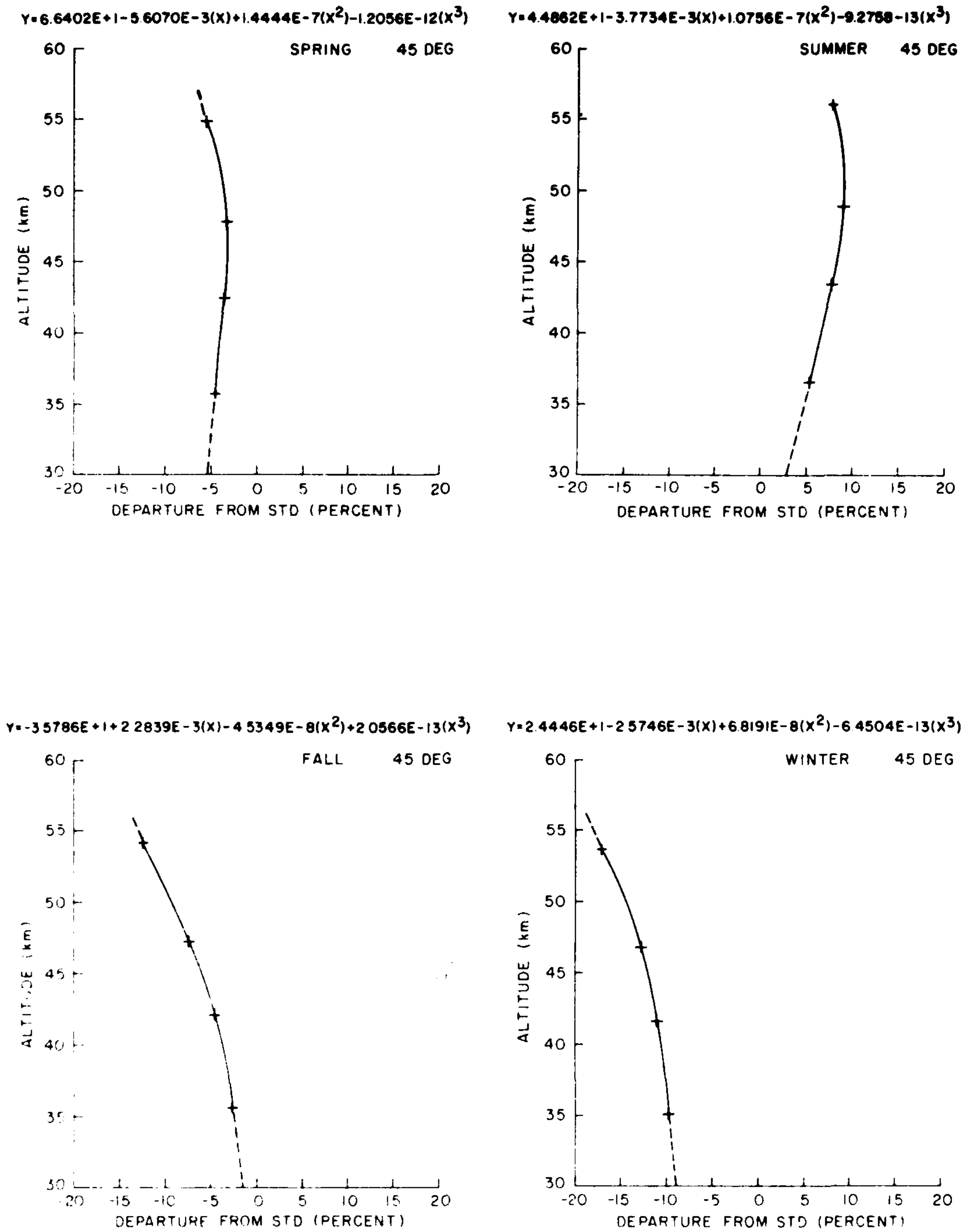


Figure 4. Third Degree Polynomial Fits to Mean Seasonal Densities for 5, 2, 1 and 0.4-mb Pressure Surfaces at a Grid-point Near 45°N

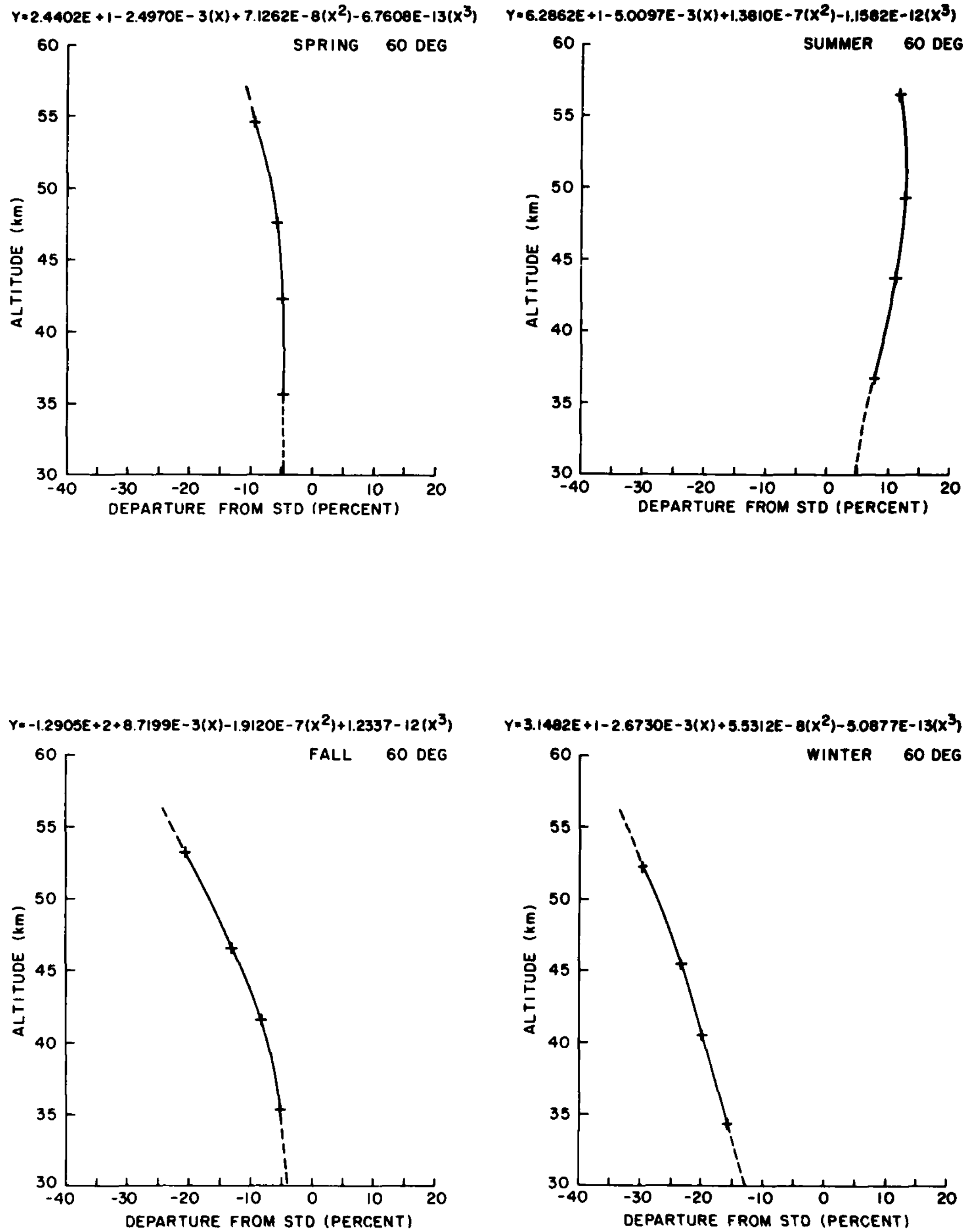


Figure 5. Third Degree Polynomial Fits to Mean Seasonal Densities for 5, 2, 1 and 0.4-mb Pressure Surfaces at a Grid-point Near 60°N

3.2 Variability of Density

A procedure analogous to that used to determine mean seasonal densities was employed to estimate standard deviations of the day-to-day variability around the seasonal means. That is, rms values, as a percent of the mean, were calculated for all 4225 grid points at the 5-, 2-, 1-, and 0.4-mb pressure levels for each season. Third-degree polynomial fits to the values at the four pressure levels result in vertical profiles of the estimated rms variations around the seasonal means for altitudes from 30 through 55 km. Examples of these data and the fitted curves are shown in Figures 6, 7 and 8 for the same locations 381 km east of 80°W longitude, near 30°N (Figure 6), near 45°N (Figure 7) and near 60°N (Figure 8). As before, third degree polynomial fits to four data points produce curves that go through every point. Again, these are preferable to quadratic fits in which curvatures are unchanging and, consequently, less realistic. Linear extensions to the curves, when and where required to reach 30 and 55 km, are shown by the dashed lines in the examples given in Figures 6, 7 and 8.

4. RESULTS

The mean seasonal grid-point densities, which were derived for constant altitudes as described in Section 3, were analyzed objectively (by computer) to construct northern hemisphere maps of mean seasonal density. Twenty-four seasonal charts were drawn, four each at 30, 35, 40, 45, 50, and 55 km; they are given in Appendix A. These computer-analyzed maps were subjectively smoothed as required to provide vertical and horizontal consistency.

Superimposed on the seasonal mean densities are standard deviations which were derived in the same manner as the mean densities, and represent estimates of the day-to-day variability around the seasonal averages. However, optimum results in determining day-to-day variability around monthly or seasonal averages require daily observations over an extended period of time. Suitable daily data are not yet available because daily charts (since 1978) are based only on satellite measurements and lack the detail needed for variability analysis.[9] Consequently, the once-weekly observations have been used to provide estimates of the standard deviation of the day-to-day variations of density around mean seasonal values. The results tend to underestimate the true variability.

Standard deviations are not shown for the winter season because temperatures, and consequently densities, are not normally distributed in winter at these altitudes,

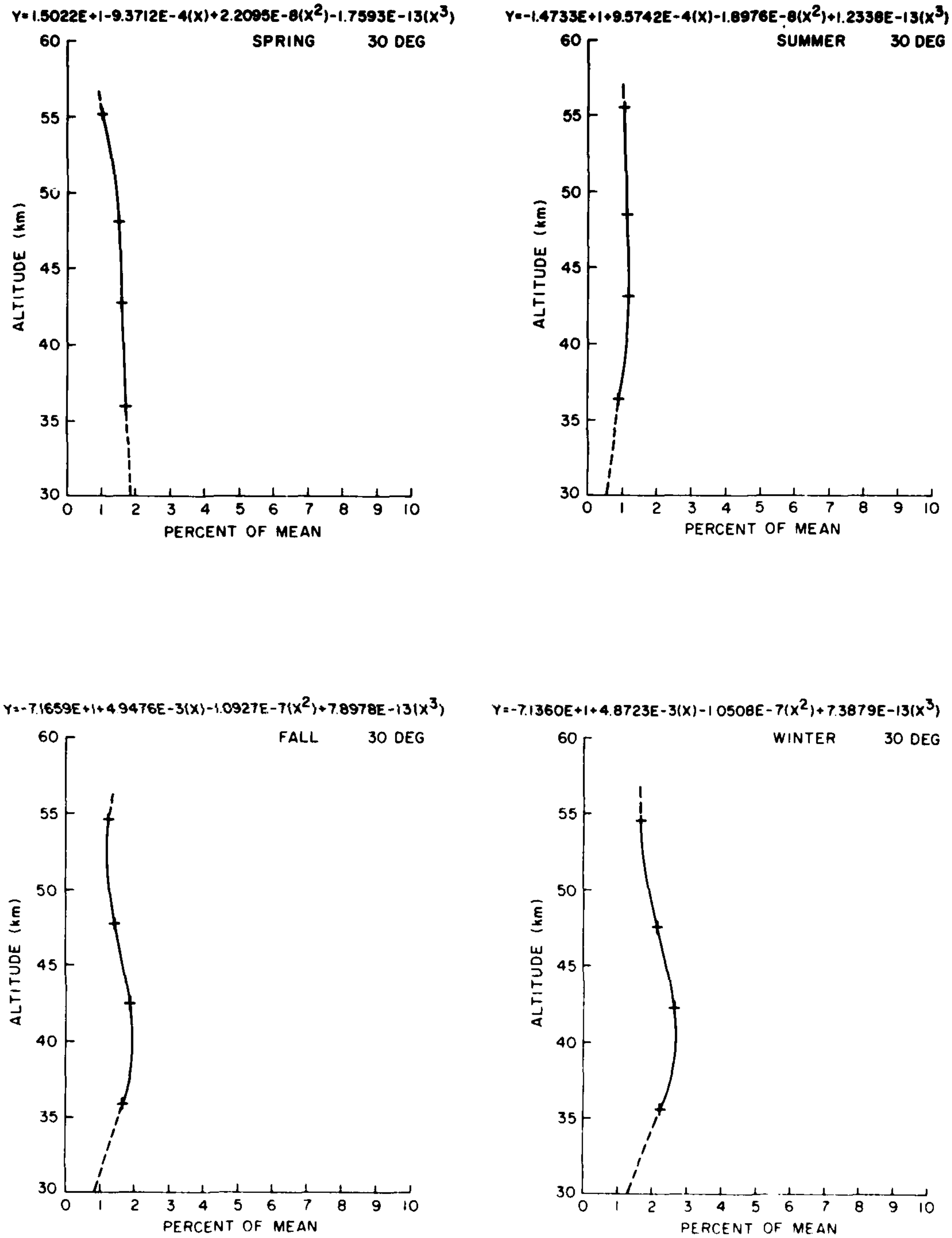


Figure 6. Third Degree Polynomial Fits to Estimated rms Density Variations for 5, 2, 1 and 0.4-mb Pressure Surfaces at a Grid-point Near 30°N

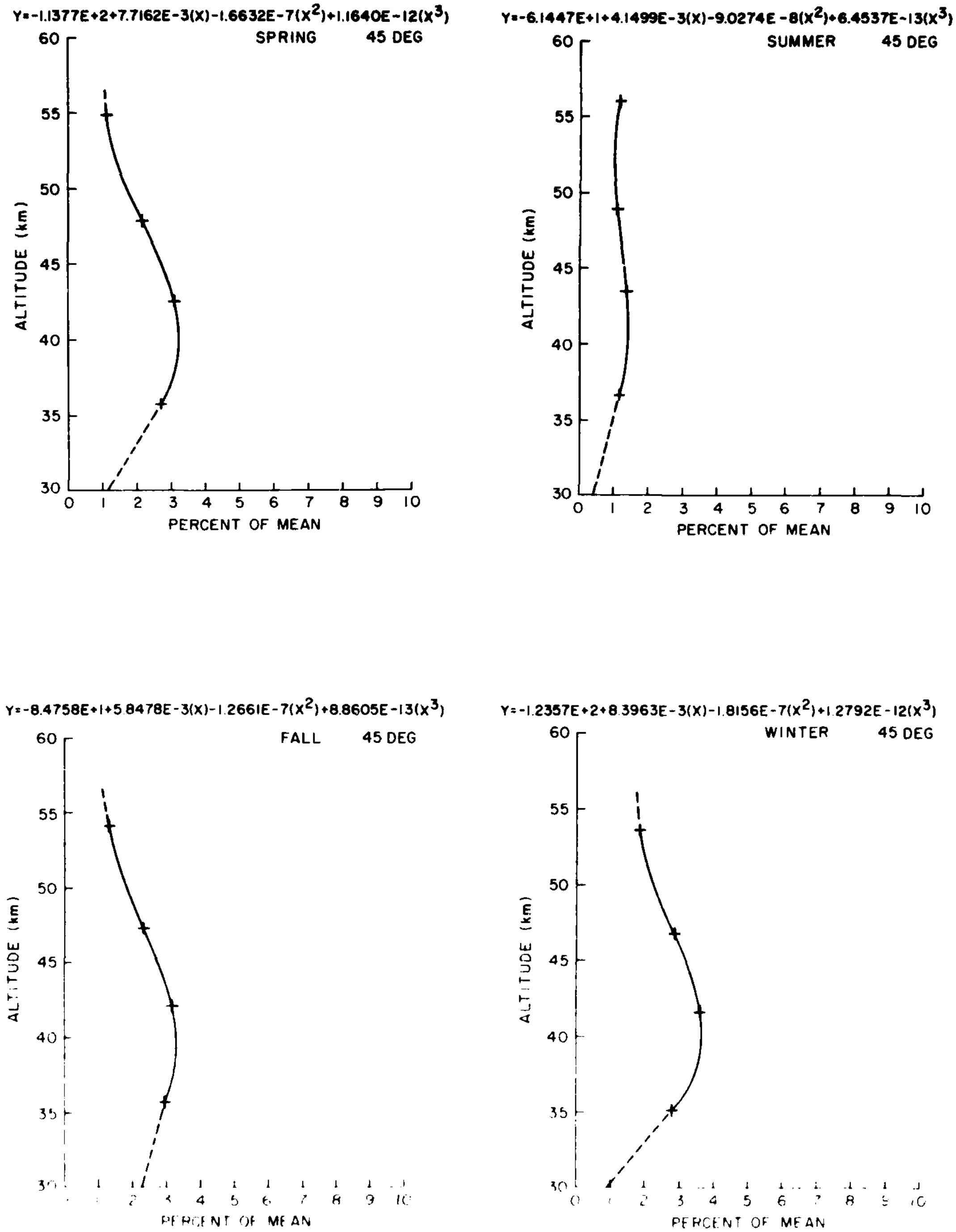


Figure 7. Third Degree Polynomial Fits to Estimated rms Density Variations for 5, 2, 1 and 0.4-mb Pressure Surfaces at a Grid-point Near 45°N

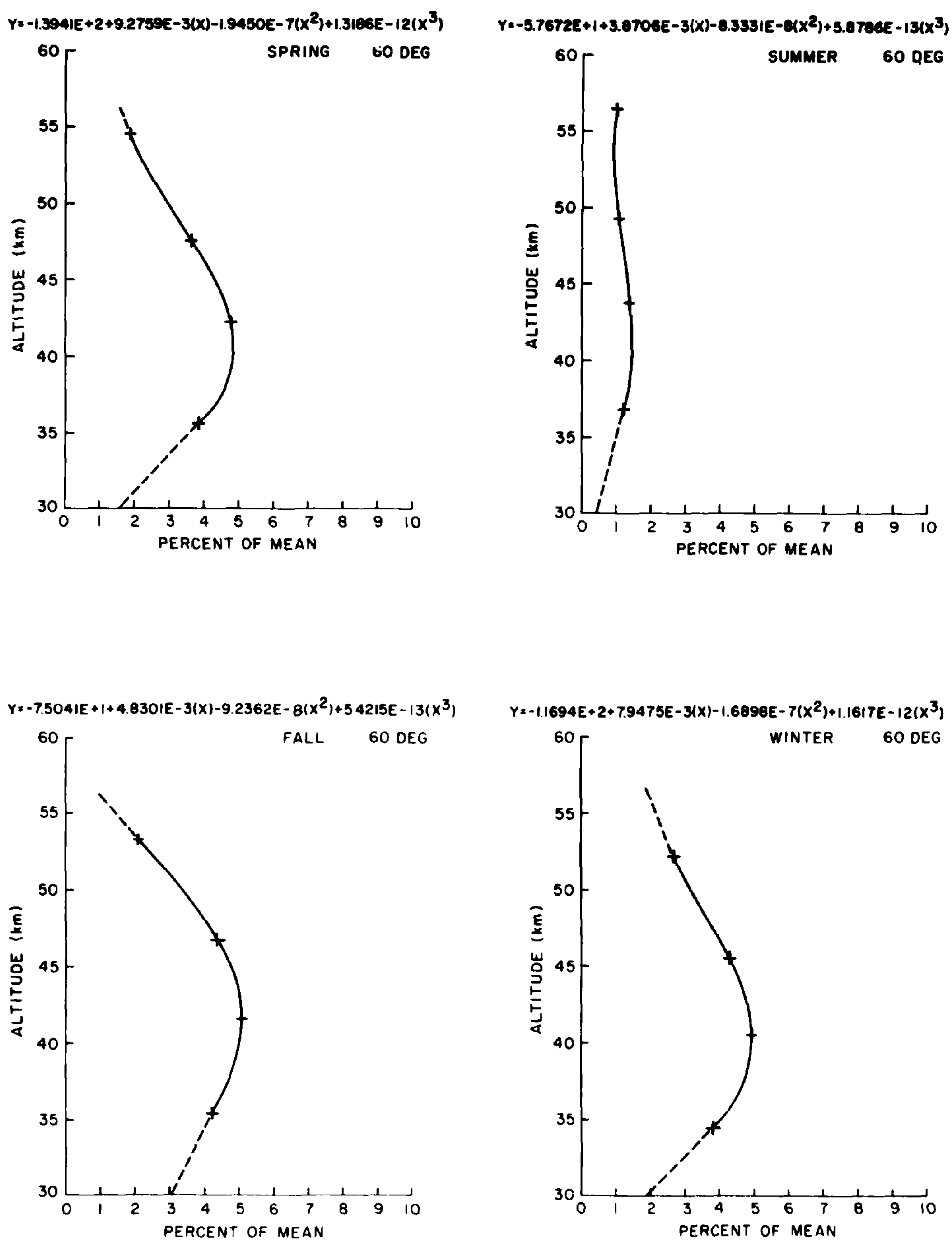


Figure 8. Third Degree Polynomial Fits to Estimated rms Density Variations for 5, 2, 1 and 0.4-mb Pressure Surfaces at a Grid-point Near 60°N

particularly in middle and high latitudes. The density distributions tend to be bimodal or rectangular rather than normal during the winter over these regions.[13,14]

Rough first estimates of day-to-day density variations for January have been made for a number of Meteorological Rocket Network stations in middle and high latitudes, and estimated 1, 10, and 20 percent extremes for latitudes 30, 45, 60, and 75°N are provided in the Air Force Reference Atmospheres.[15] Although there can be considerable change in density distribution with longitude in winter, especially poleward of 40°N, the 1, 10, and 20 percent values are presented in that report as being representative of the type of variations that can be expected to occur at those latitudes. They are reproduced herein in Tables 1, 2, 3, and 4 for altitudes 30 through 55 km.

To test the validity of the derived density maps shown in the appendix, mean seasonal densities obtained from these maps were compared with values obtained from the Meteorological Rocket Network data. The results are given in Table 5. Values for White Sands, Wallops Island, and Churchill are in general agreement in that trends with season, latitude and altitude are similar. The values at Churchill in winter are nearly identical, even though the map data are based on only 46 months of observations from July 1976 through April 1980.

5. REMARKS

This preliminary atlas of northern hemisphere density in the upper stratosphere contains 24 maps of mean seasonal density for altitudes between 30 and 55 km, and includes estimated standard deviations of the day-to-day variability around the seasonal means. It can serve as the precursor of a more extensive and detailed atlas of atmospheric density for altitudes above radiosonde levels. Perhaps as little as four additional years of observations at constant pressure levels will afford sufficient data for application of the method described in this report to provide a more useful and accurate presentation of the climatology of density in the upper stratosphere and lower mesosphere.

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13. Cole, A.E., and Kantor, A.J. (1974) Periodic Oscillations in the Stratosphere and Mesosphere, AFCRL-TR-74-0504, AD A003396.

14. Valley, S.L., (Ed.) (1965) Handbook of Geophysics and Space Environments, AFCRL.

15. Cole, A.E., and Kantor, A.J. (1978) Air Force Reference Atmospheres, AFGL-TR-[illegible], AD [illegible]

Table 1. High and Low Percentiles of Density in January at 30°N, Given as Percentage Departures From U.S. Standard Atmosphere, 1976

Altitude (km)	1%		10%		20%		U.S. Std Density ($kg\ m^{-3}$)
	High	Low	High	Low	High	Low	
30	+2	-10	-2	-8	-3	-6	1.8410
35	+3	-12	0	-8	-1	-6	8.4634-3
40	+2	-10	+1	-7	0	-5	3.9957
45	+8	-10	+3	-7	+2	-5	1.9663
50	+12	-8	+7	-4	+5	-2	1.0269
55	+9	-10	+5	-6	+3	-4	5.6810-4

Table 2. High and Low Percentiles of Density in January at 45°N, Given as Percentage Departures From U.S. Standard Atmosphere, 1976

Altitude (km)	1%		10%		20%		U.S. Std Density ($kg\ m^{-3}$)
	High	Low	High	Low	High	Low	
30	+1	-17	-2	-13	-4	-9	1.8410
35	+2	-20	-2	-16	-4	-12	8.4634-3
40	+5	-23	0	-17	-4	-13	3.9957
45	+8	-22	+2	-16	-3	-14	1.9663
50	+11	-20	+4	-16	-3	-14	1.0269
55	+9	-25	+2	-18	-4	-16	5.6810-4

Table 3. High and Low Percentiles of Density in January at 60°N, Given as Percentage Departures From U.S. Standard Atmosphere, 1976

Altitude (km)	1%		10%		20%		U.S. Std Density (kg m^{-3})
	High	Low	High	Low	High	Low	
30	+7	-32	+2	-18	-2	-15	1.8410
35	+8	-35	+3	-27	-3	-19	8.4634-3
40	+10	-36	+5	-30	-4	-20	3.9957
45	+12	-39	+5	-34	-10	-24	1.9663
50	+14	-43	+3	-36	-15	-29	1.0269
55	+9	-48	-10	-39	-20	-35	5.6810-4

Table 4. High and Low Percentiles of Density in January at 75°N, Given as Percentage Departures From U.S. Standard Atmosphere, 1976

Altitude (km)	1%		10%		20%		U.S. Std Density (kg m^{-3})
	High	Low	High	Low	High	Low	
30	-4	-36	-9	-26	-16	-24	1.8410
35	0	-43	-10	-32	-16	-30	8.4634-3
40	+4	-48	-9	-38	-16	-38	3.9957
45	+8	-52	-6	-45	-16	-39	1.9663
50	+4	-56	-8	-48	-20	-42	1.0269
55	+5	-65	-10	-56	-23	-50	5.6810-4

Table 5. Comparison of Mean Seasonal Density (Percent of Standard) Obtained From Meteorological Rocket Network (MRN) Data (1969-1976) With Mean Seasonal Density Obtained From Maps

Altitude (km)	White Sands (32^{o}N)				Wallops Island (38^{o}N)				Churchill (59^{o}N)			
	Winter		Summer		Winter		Summer		Winter		Summer	
	MRN	Maps	MRN	Maps	MRN	Maps	MRN	Maps	MRN	Maps	MRN	Maps
	%		%		%		%		%		%	
30	-2.6	-7	4.3	1	-4.7	-5	4.6	1	-8.1	-10	6.0	5
40	-3.0	-6	7.7	2	-5.2	-6	9.5	3	-13.4	-15	12.5	8
50	0.6	-6	12.9	2	-1.8	-5	14.4	4	-22.6	-22	18.6	12

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15. Cole, A.E., and Kantor, A.J. (1978) Air Force Reference Atmospheres, AFGL-TR-78-0051, AD 058505.

Appendix A

Mean Seasonal Density Maps for the Northern Hemisphere at Altitudes From 30 Through 55 km

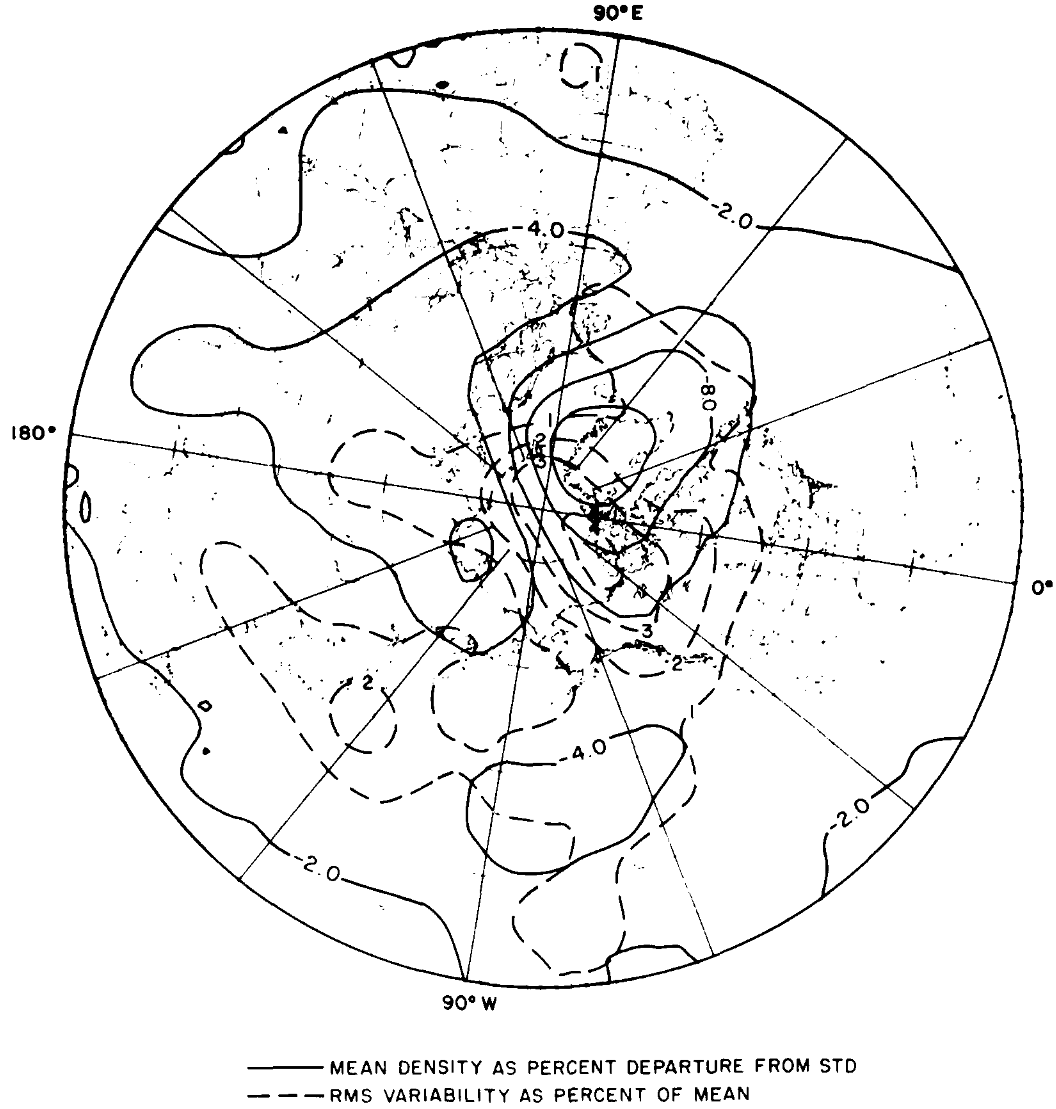


Figure A1. Density and rms Variability of Density at 30 km in the Spring

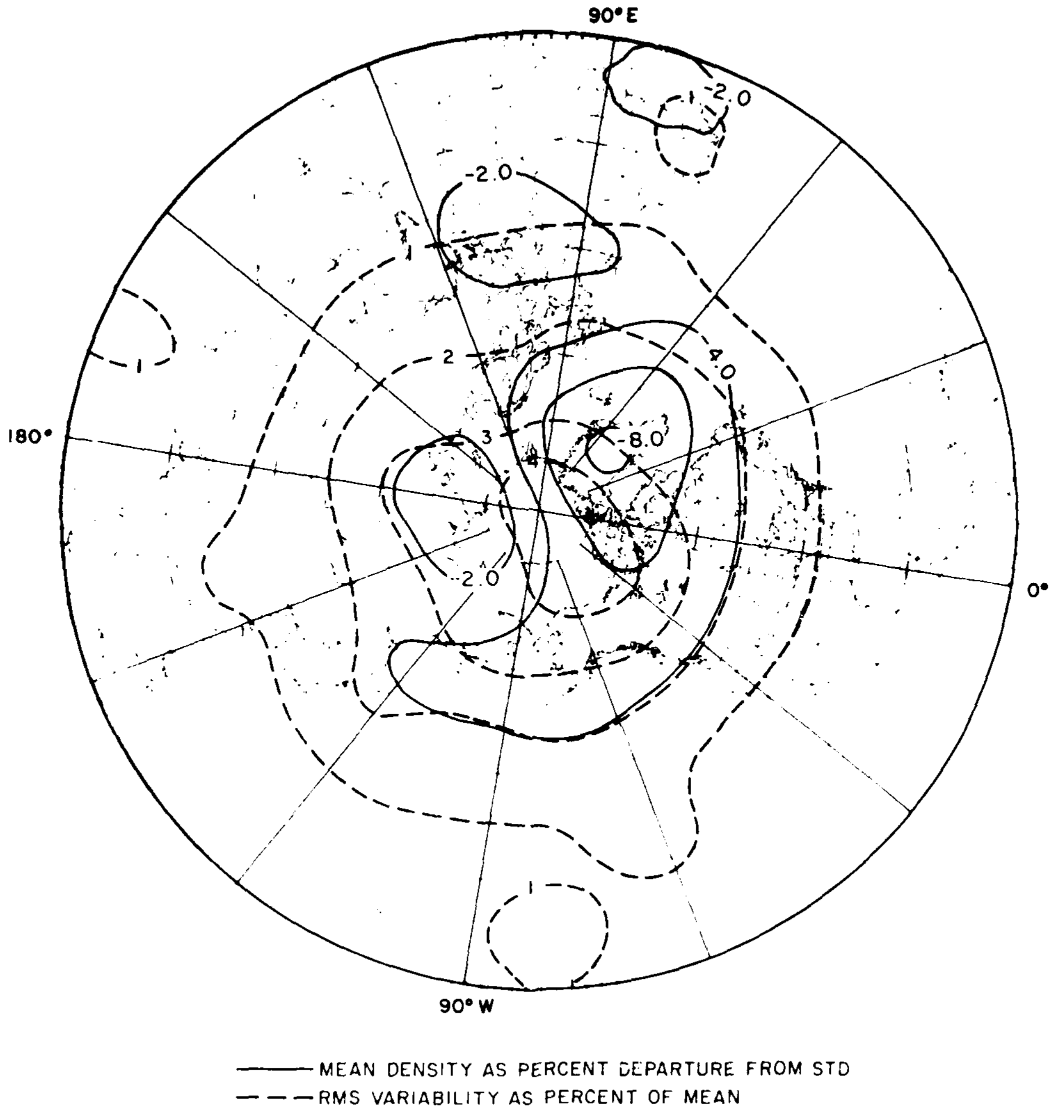


Figure A2. Density and rms Variability of Density at 35 km in the Spring

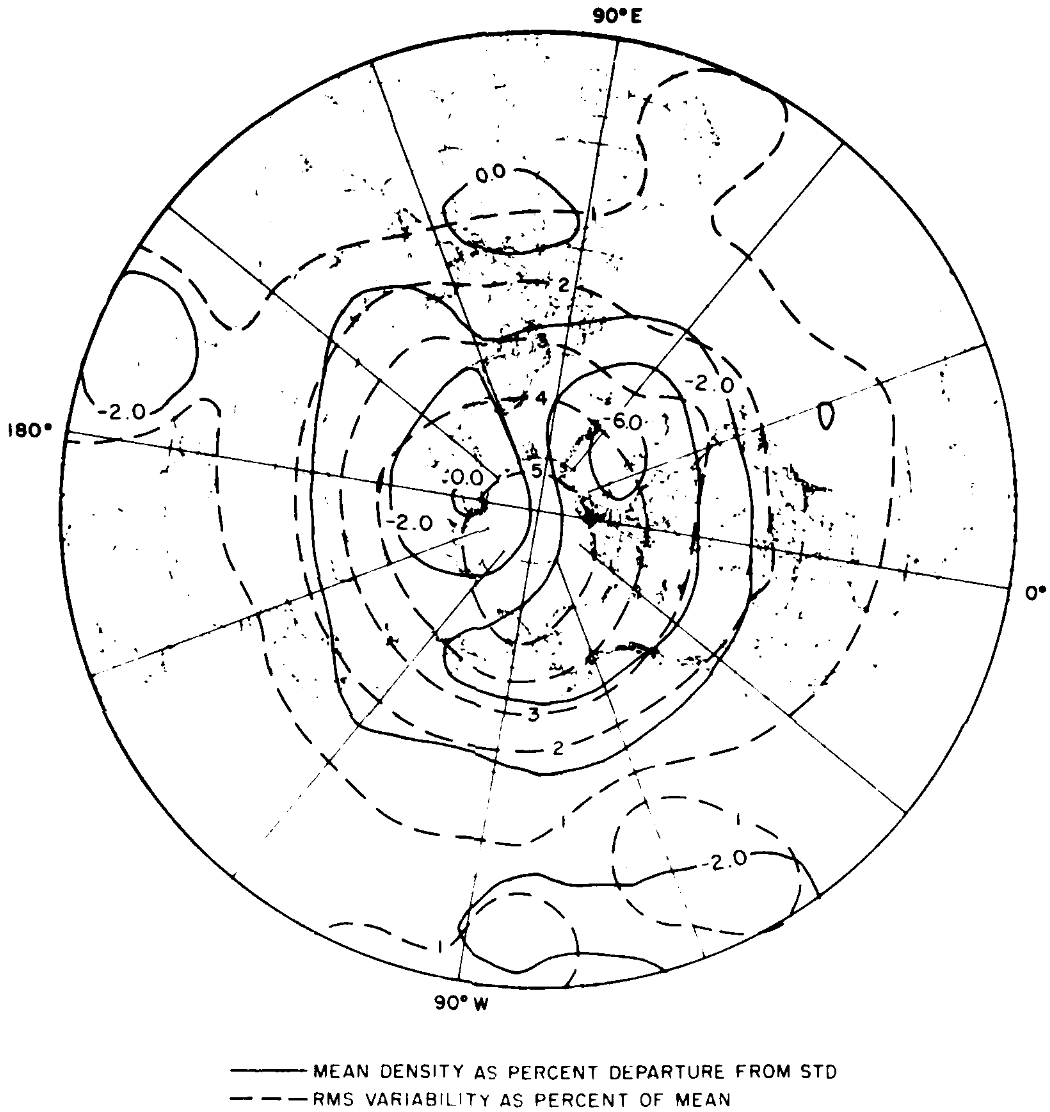


Figure A3. Density and rms Variability of Density at 40 km in the Spring

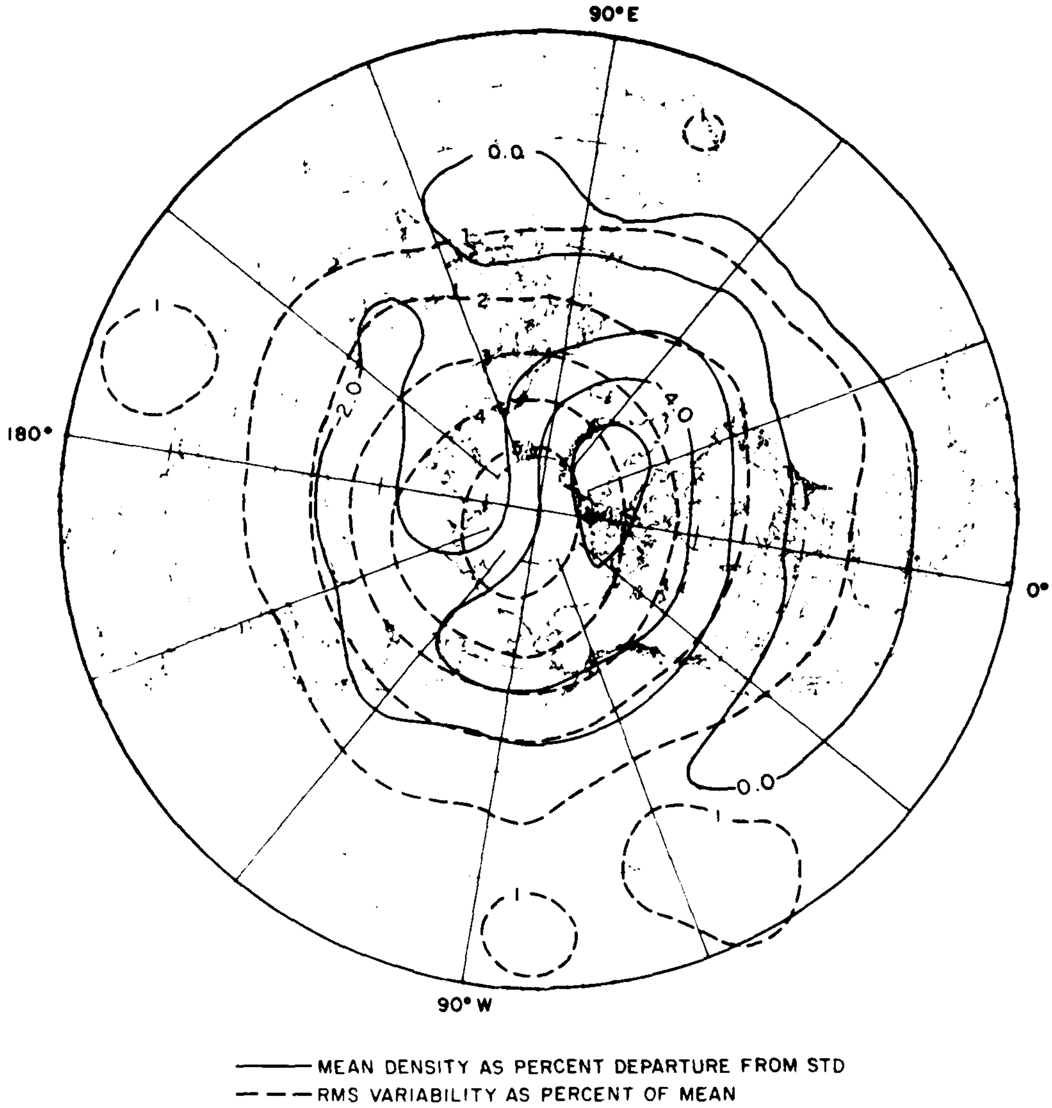


Figure A4. Density and rms Variability of Density at 45 km in the Spring

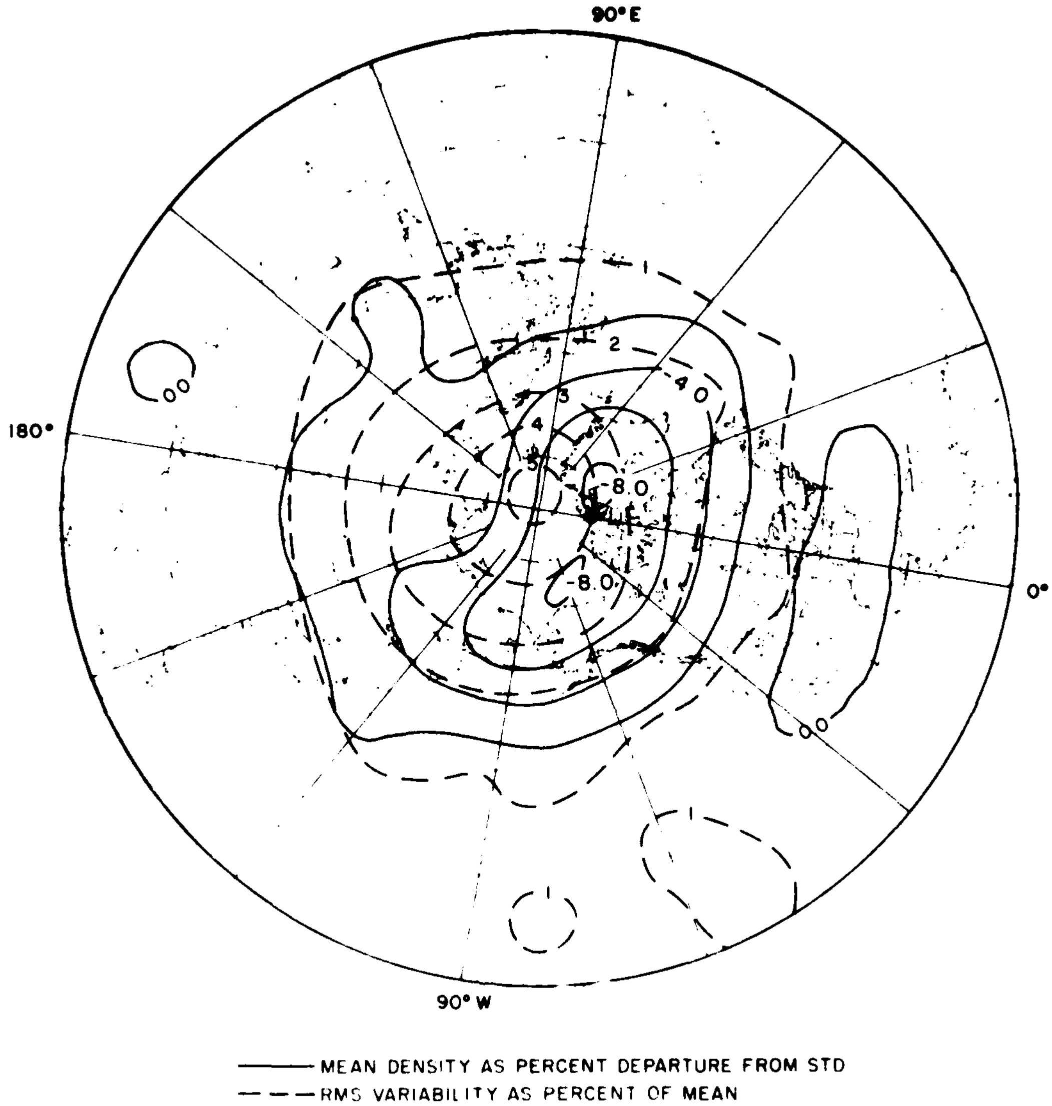


Figure A5. Density and rms Variability of Density at 50 km in the Spring

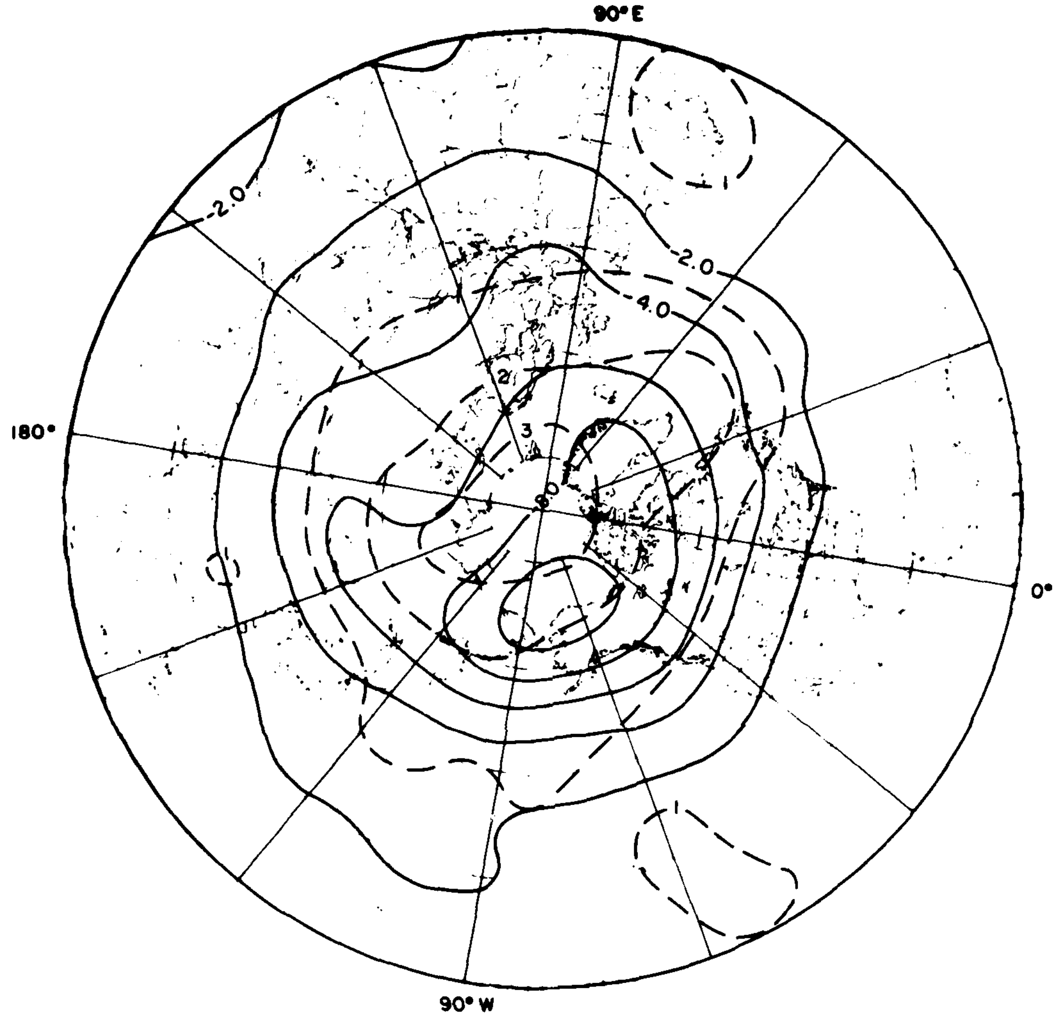


Figure A6. Density and rms Variability of Density at 55 km in the Spring

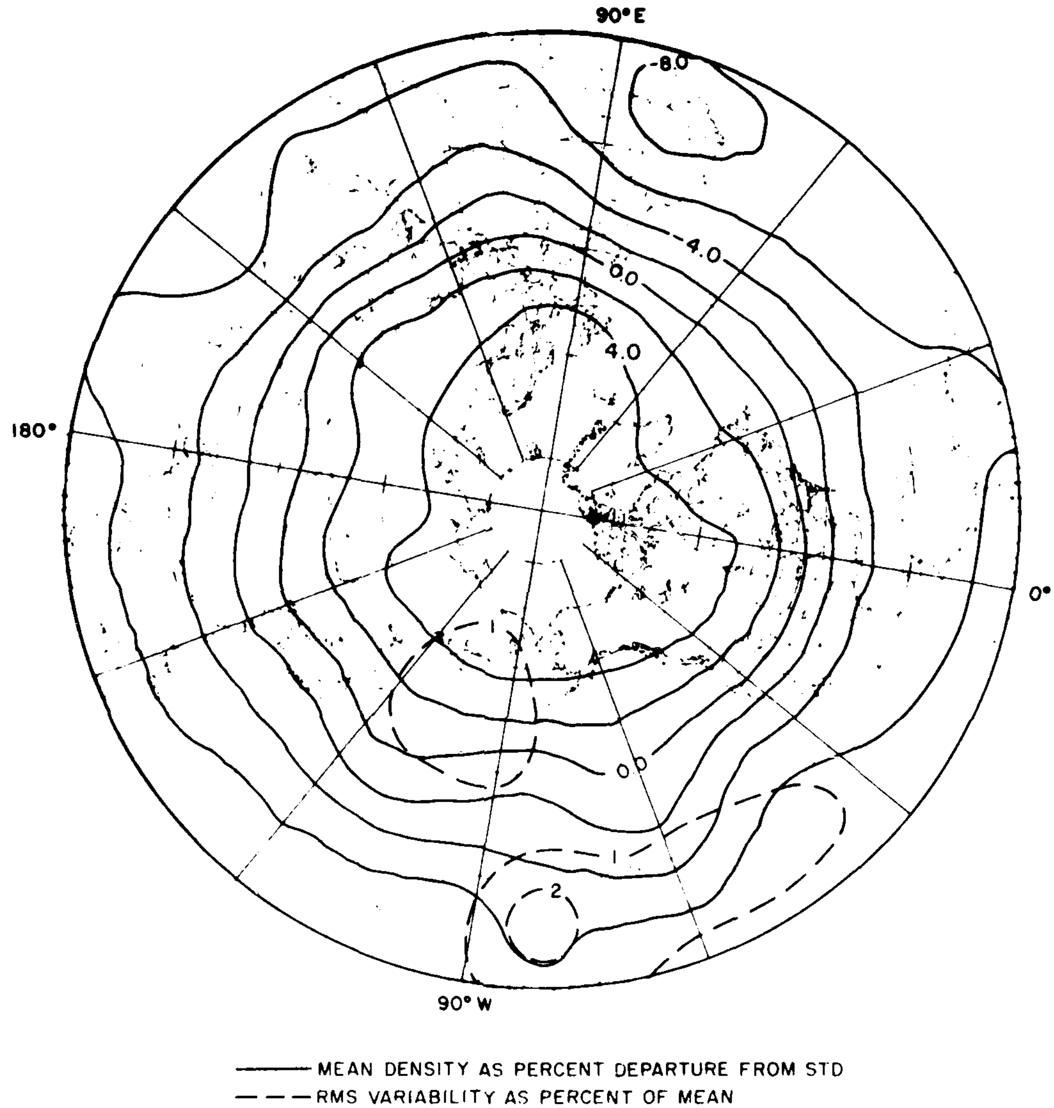


Figure A7. Density and rms Variability of Density at 30 km in the Summer

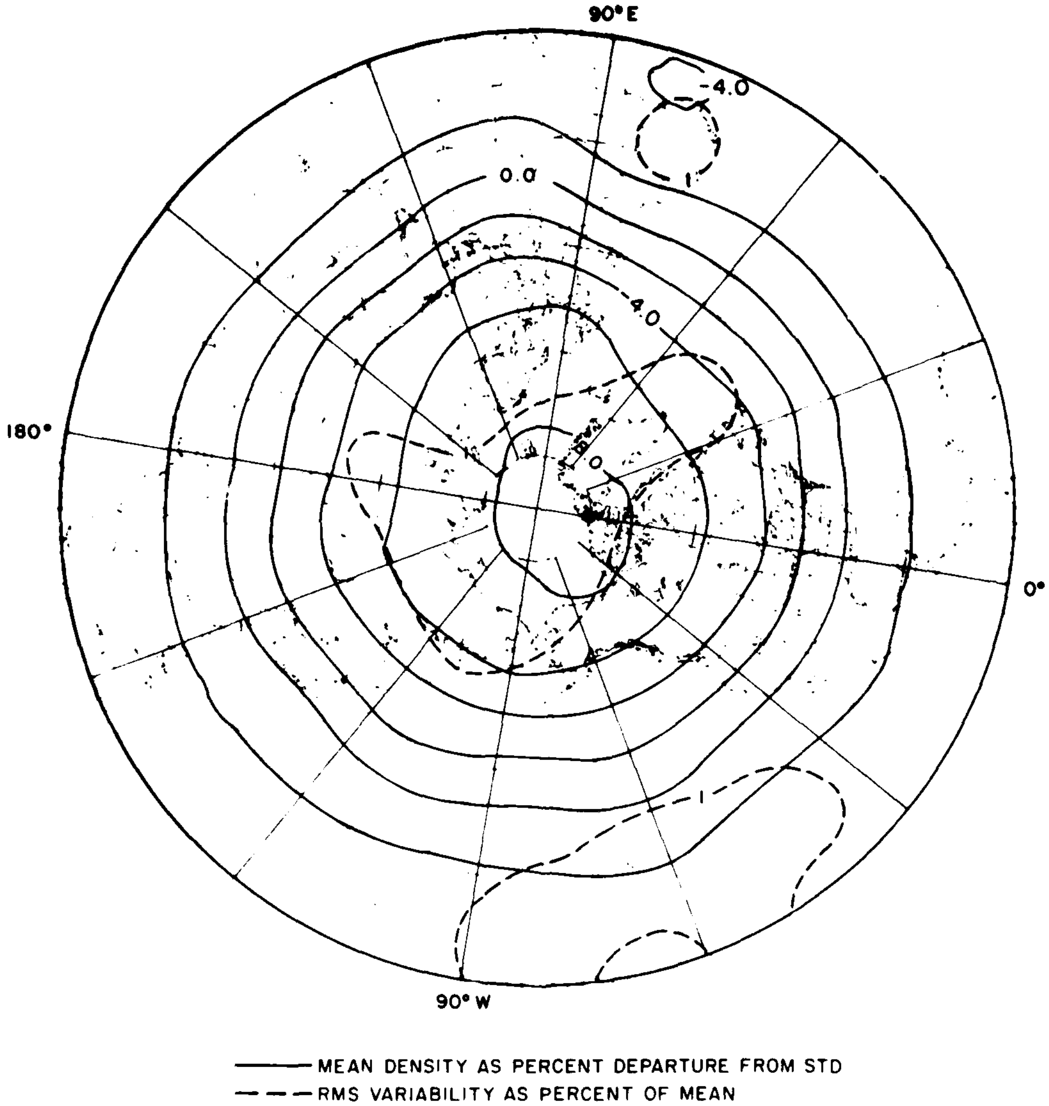
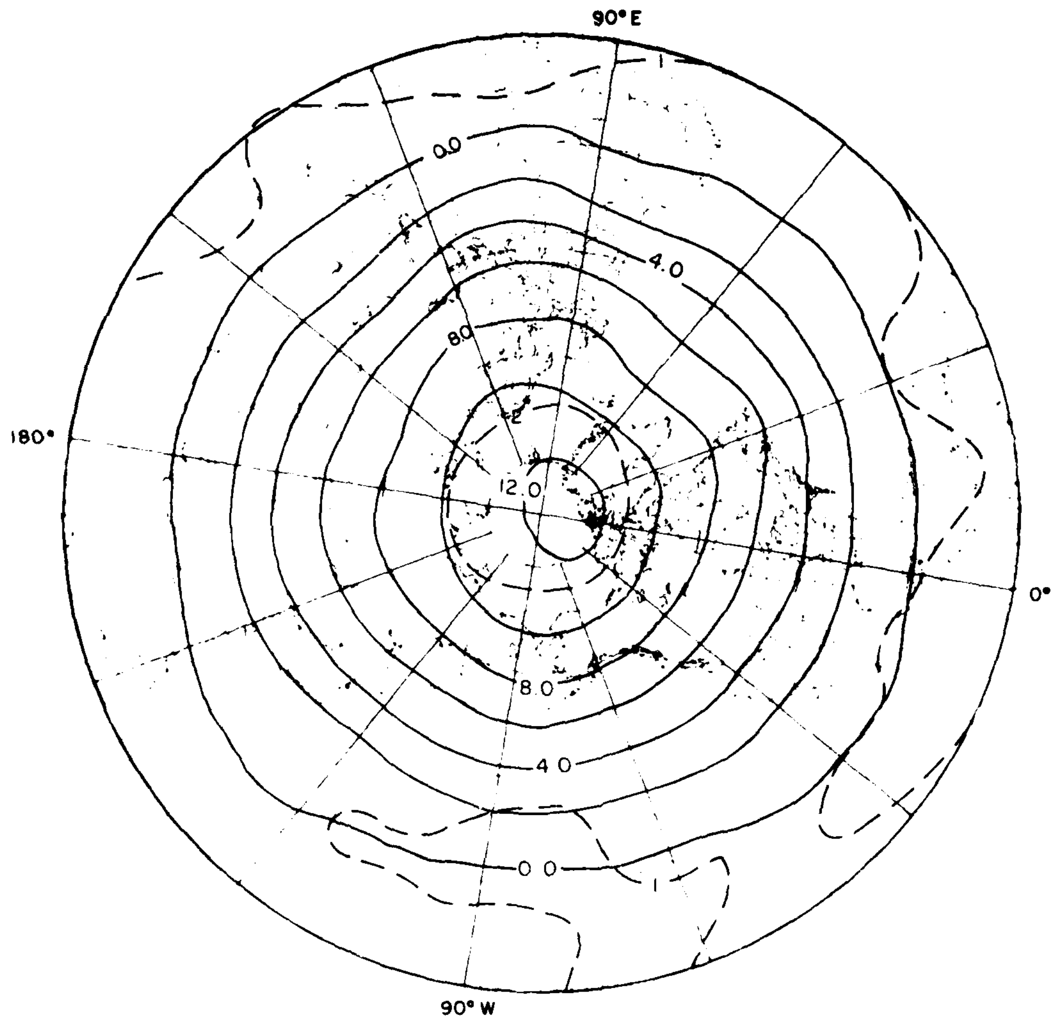


Figure A8. Density and rms Variability of Density at 35 km in the Summer



——— MEAN DENSITY AS PERCENT DEPARTURE FROM STD
— — — RMS VARIABILITY AS PERCENT OF MEAN

Figure A9. Density and rms Variability of Density at 40 km in the Summer

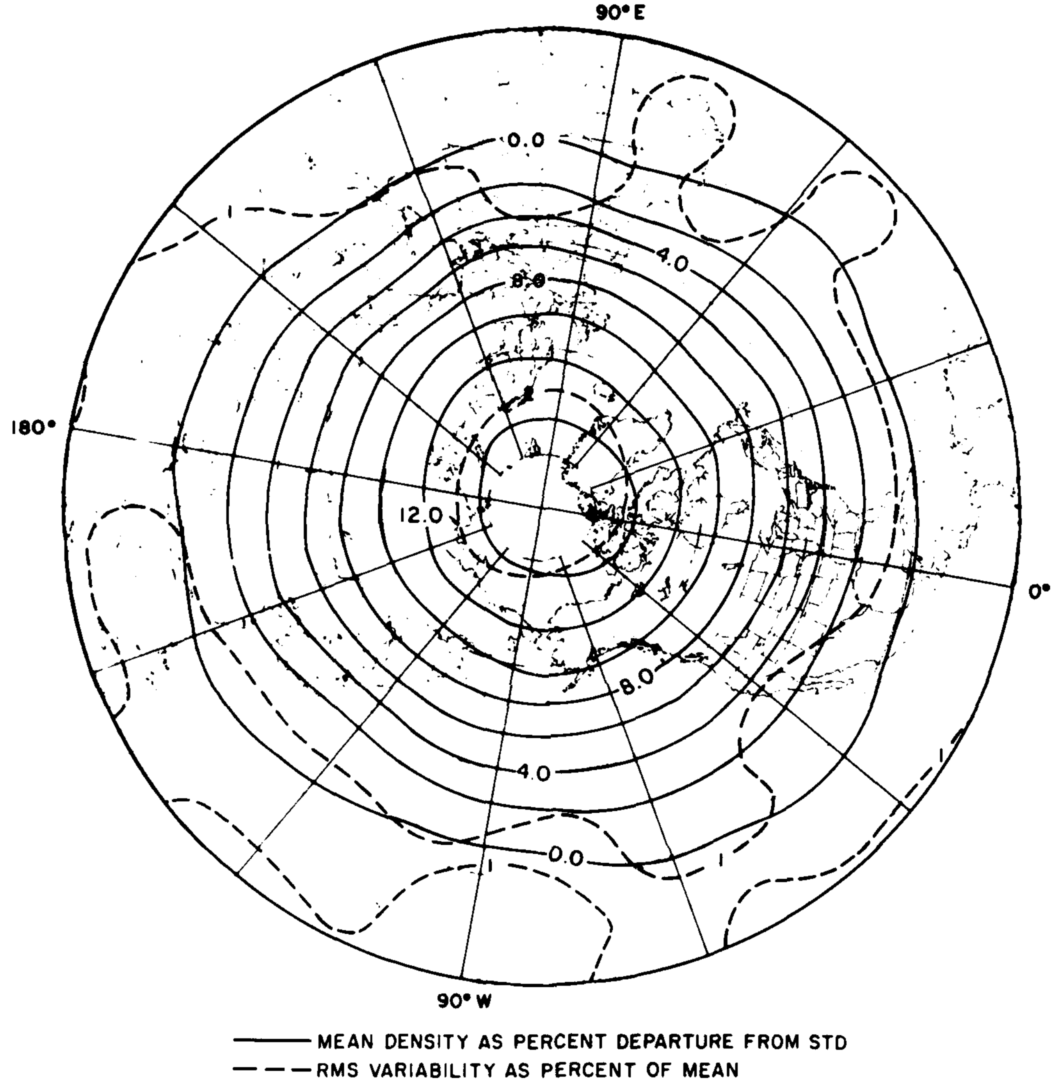
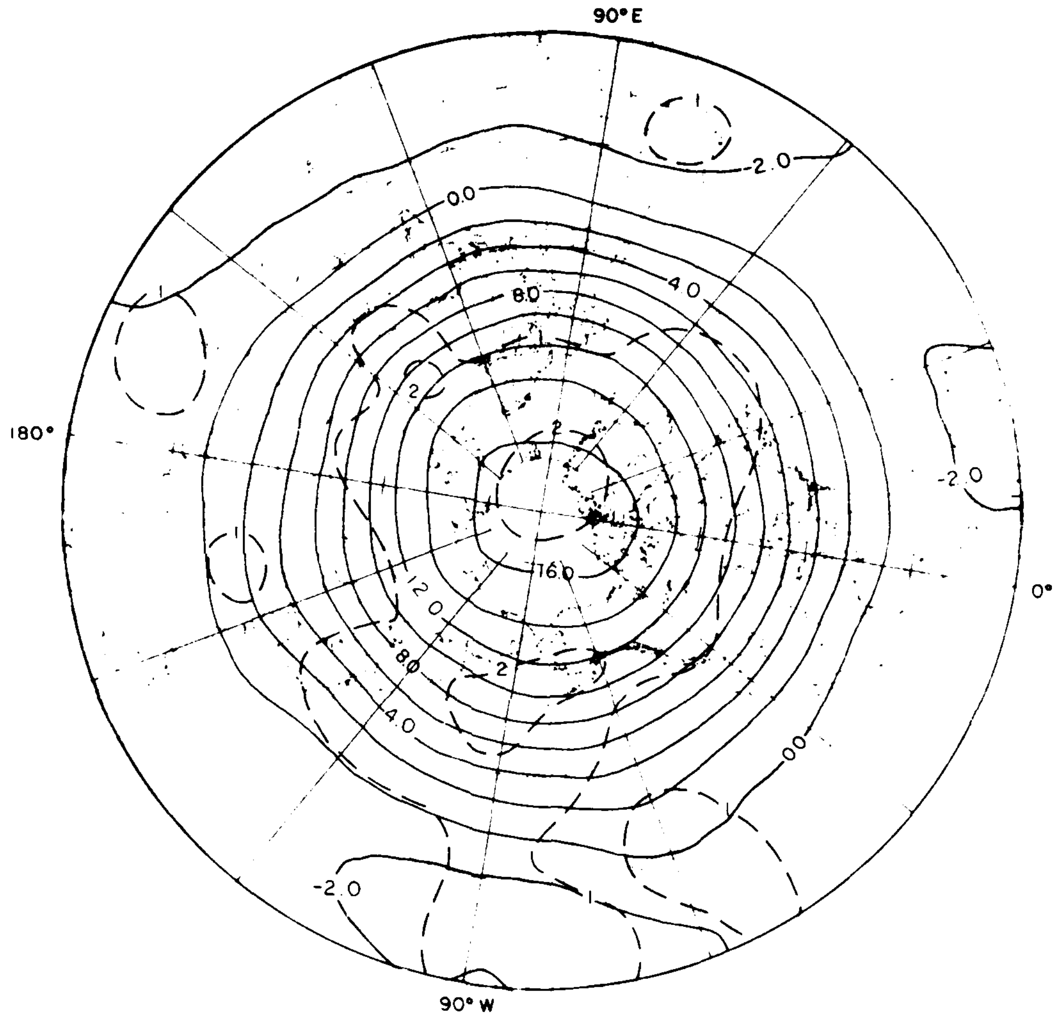


Figure A10. Density and rms Variability of Density at 45 km in the Summer



MEAN DENSITY AS PERCENT DEPARTURE FROM STD
RMS VARIABILITY AS PERCENT OF MEAN

Figure V11. Density and rms Variability of Density at 50 km in the Summer

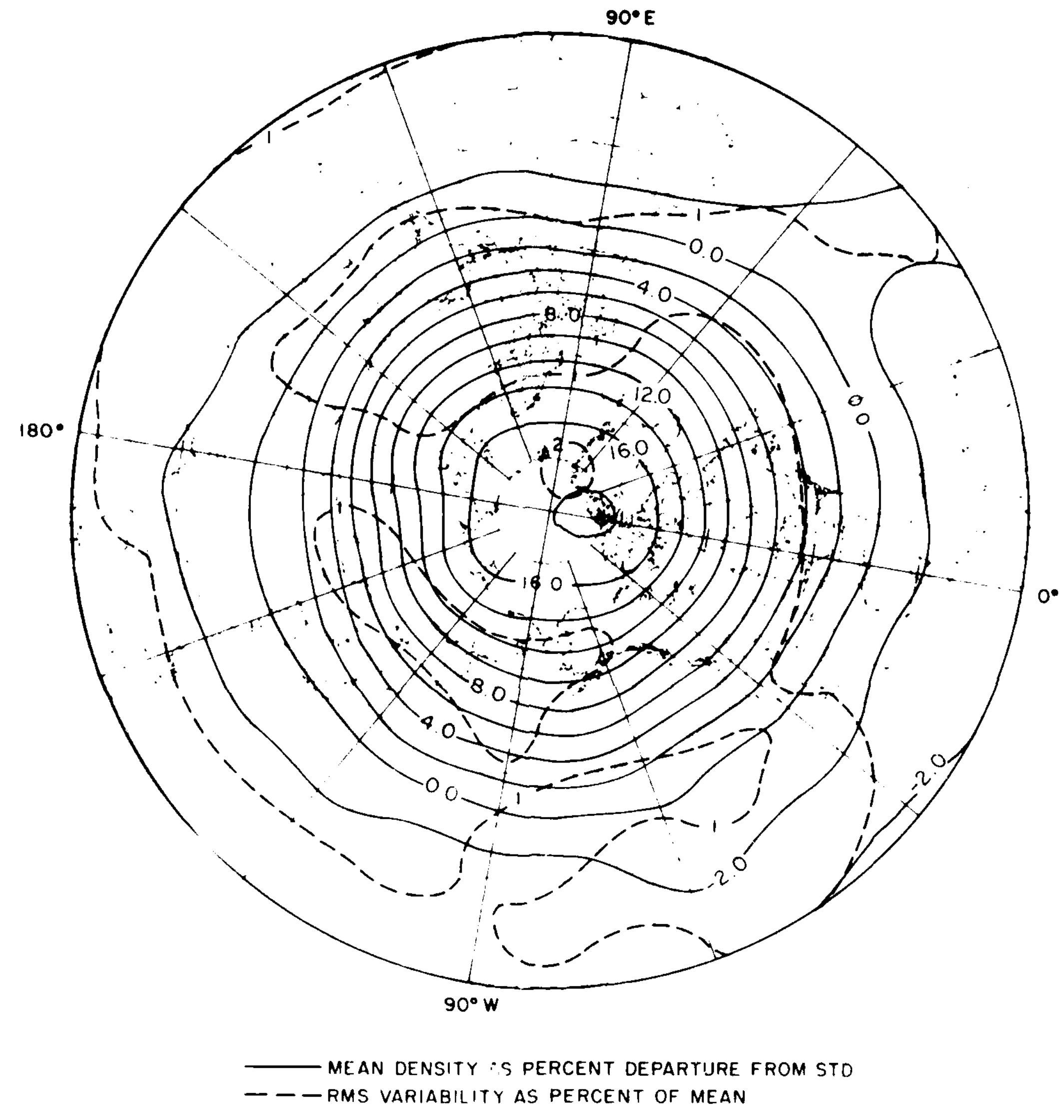


Figure A12. Density and rms Variability of Density at 55 km in the Summer

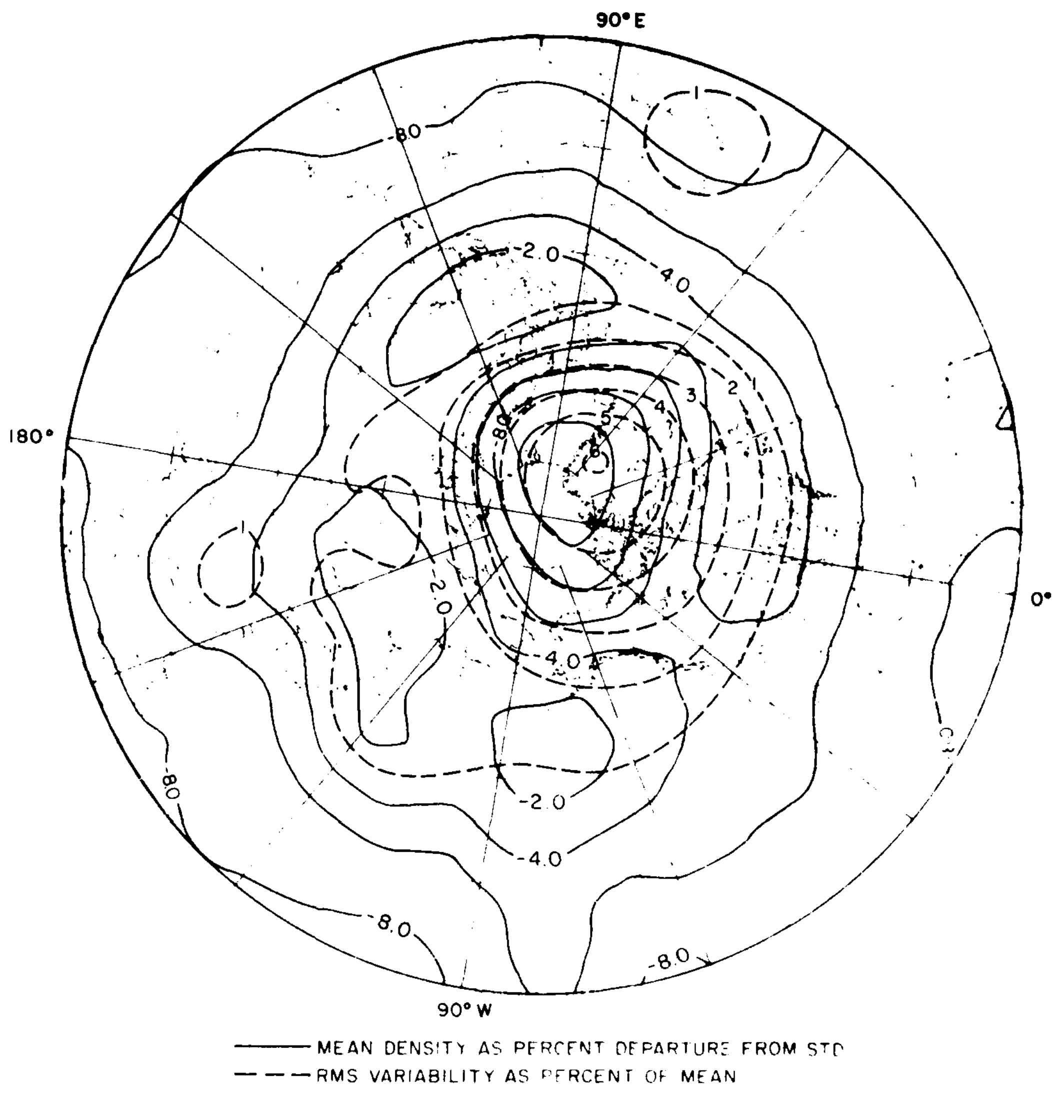


Figure A13. Density and rms Variability of Density at 30 km in the Fall

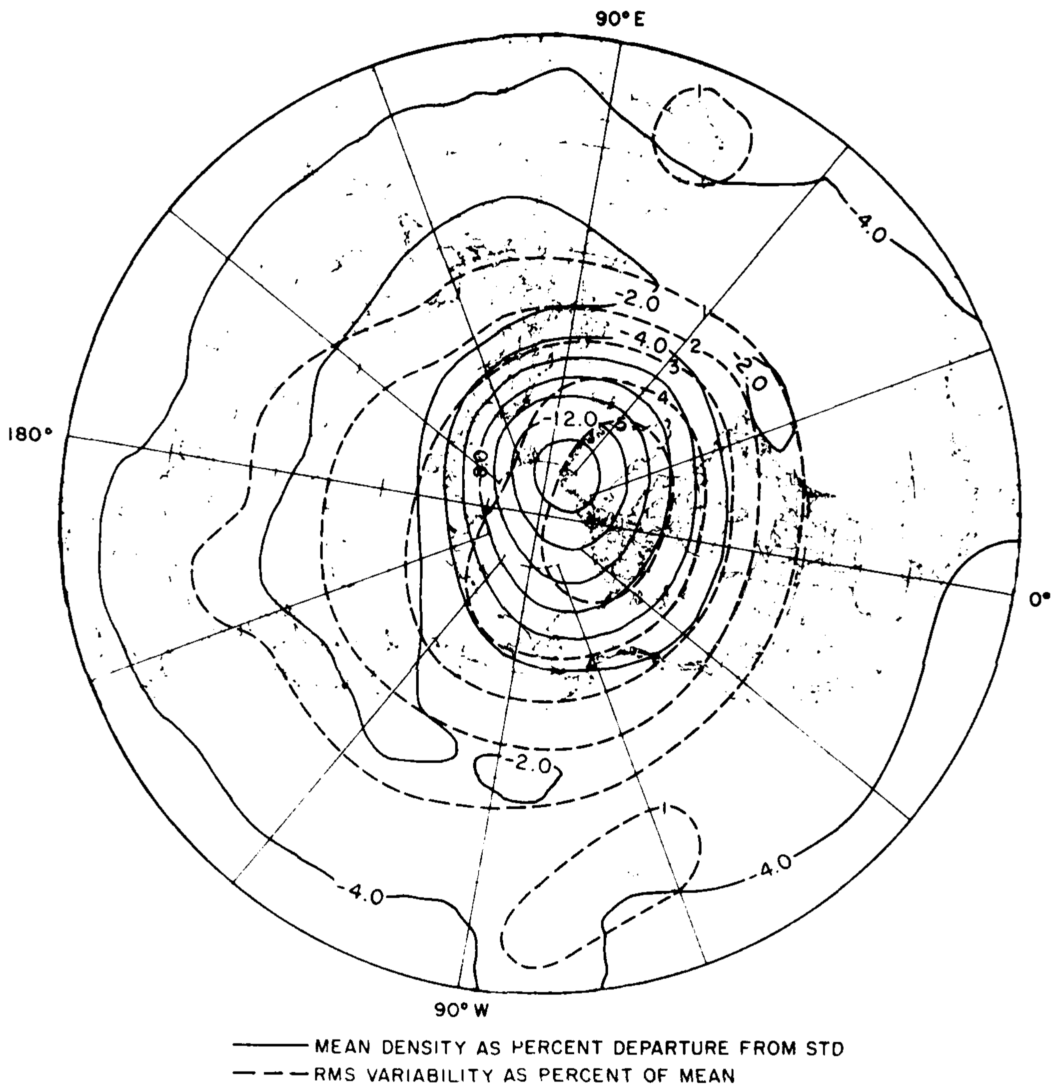


Figure A14. Density and rms Variability of Density at 35 km in the Fall

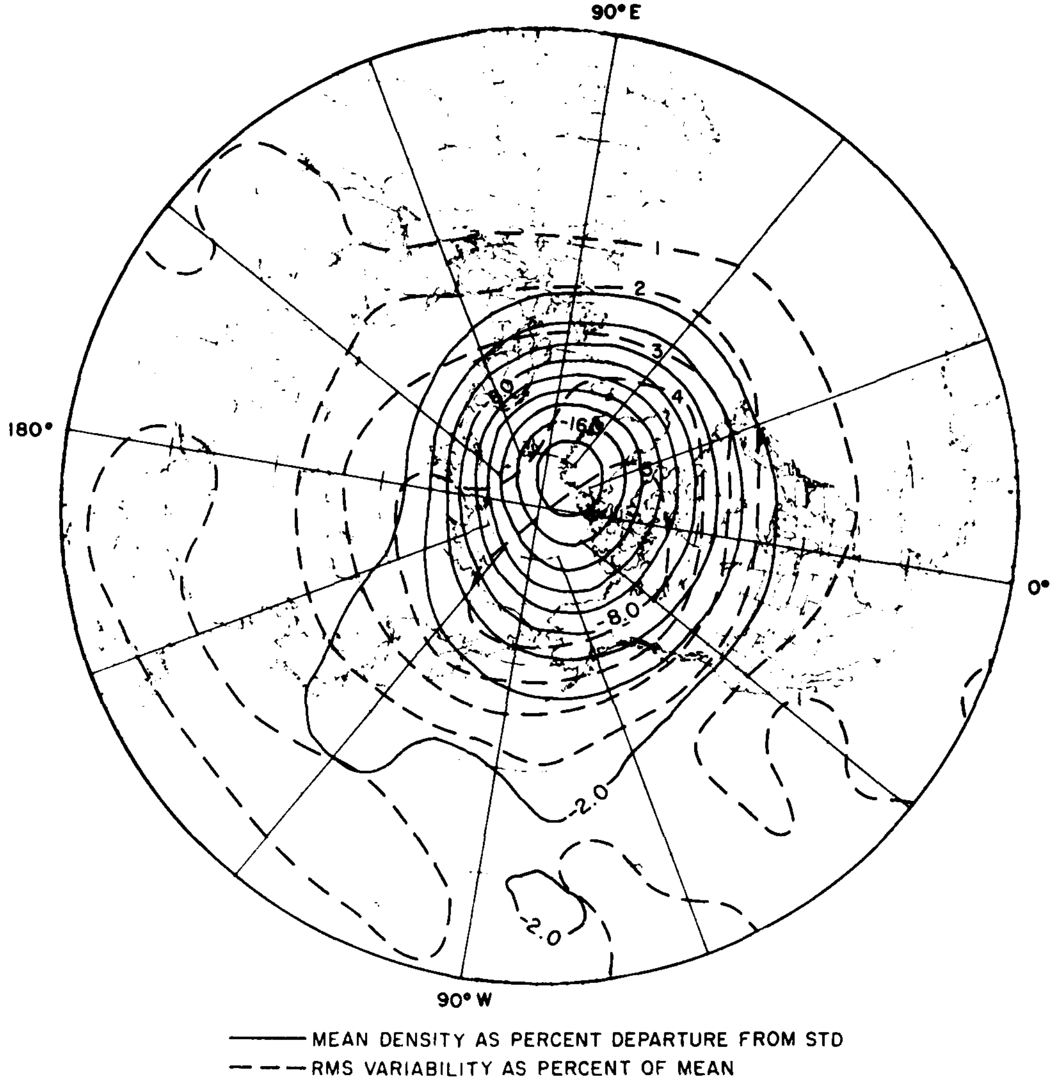


Figure A15. Density and rms Variability of Density at 40 km in the Fall

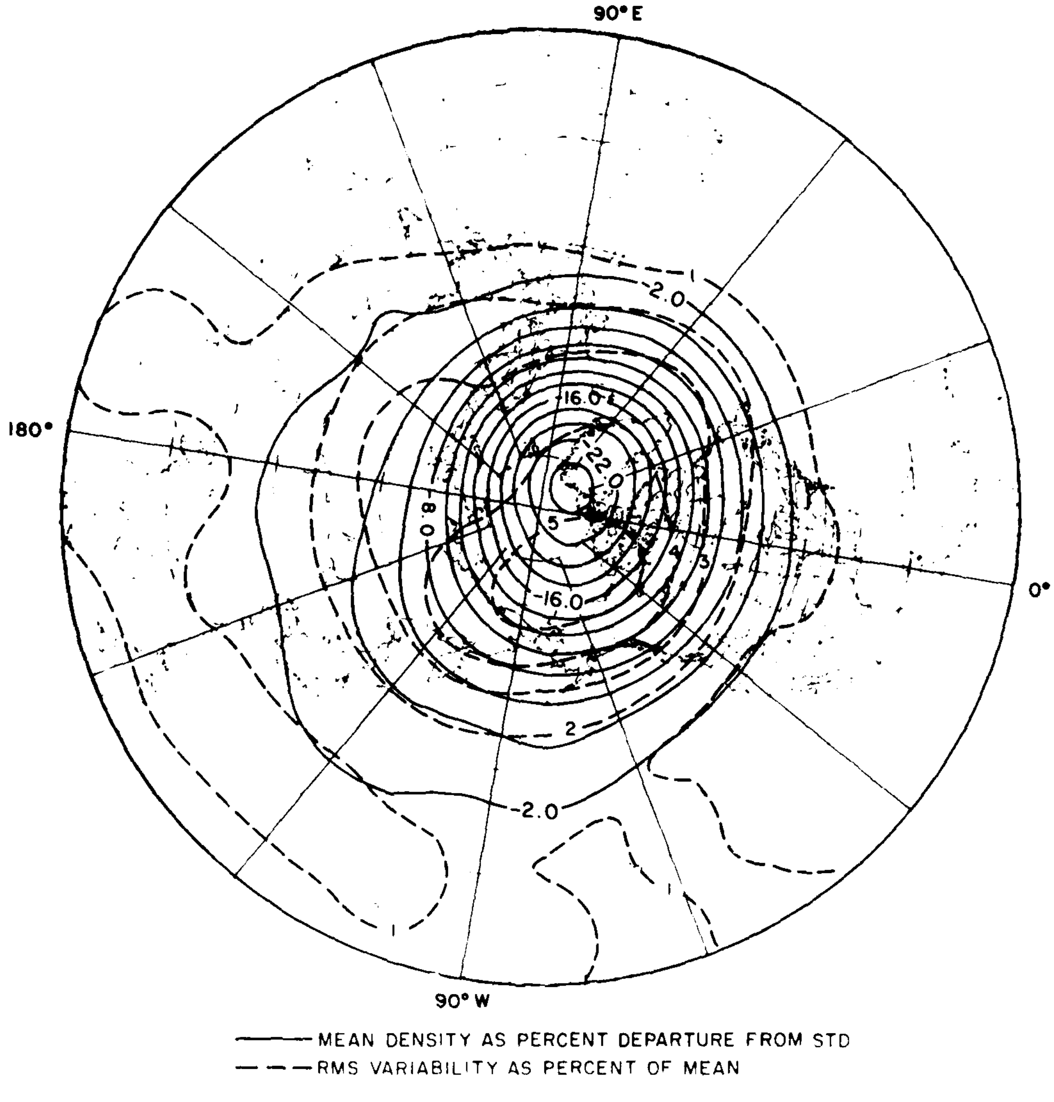
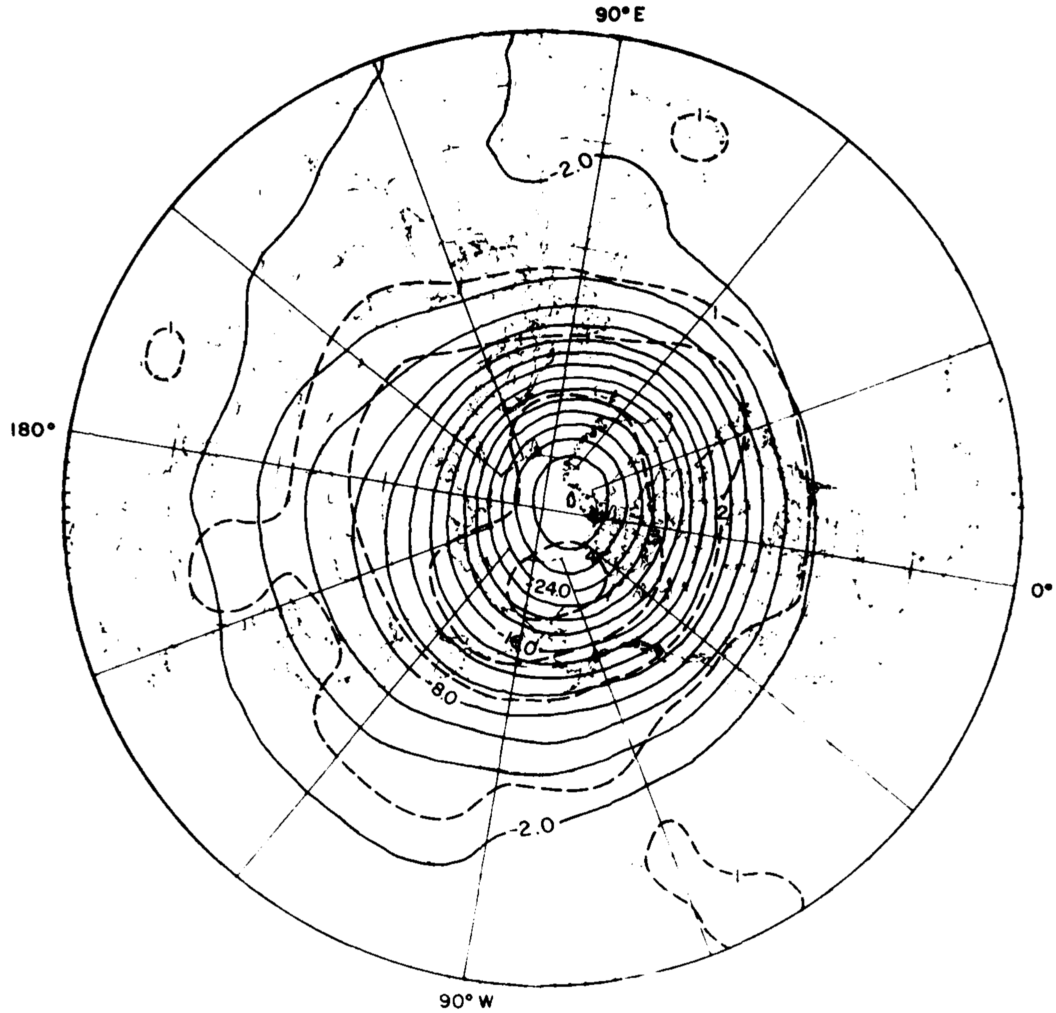


Figure A16. Density and rms Variability of Density at 45 km in the Fall



——— MEAN DENSITY AS PERCENT DEPARTURE FROM STD
— — — RMS VARIABILITY AS PERCENT OF MEAN

Figure A17. Density and rms Variability of Density at 50 km in the Fall

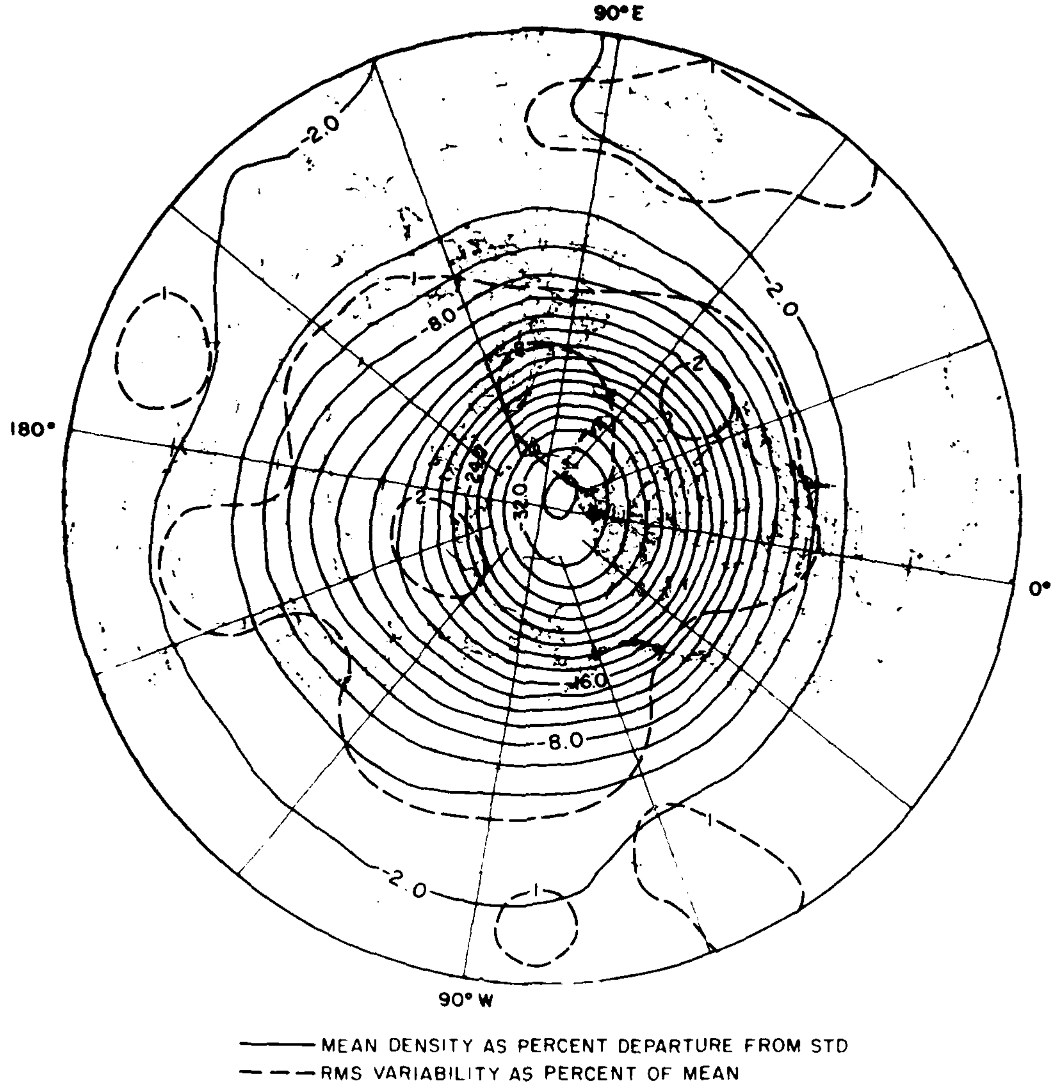
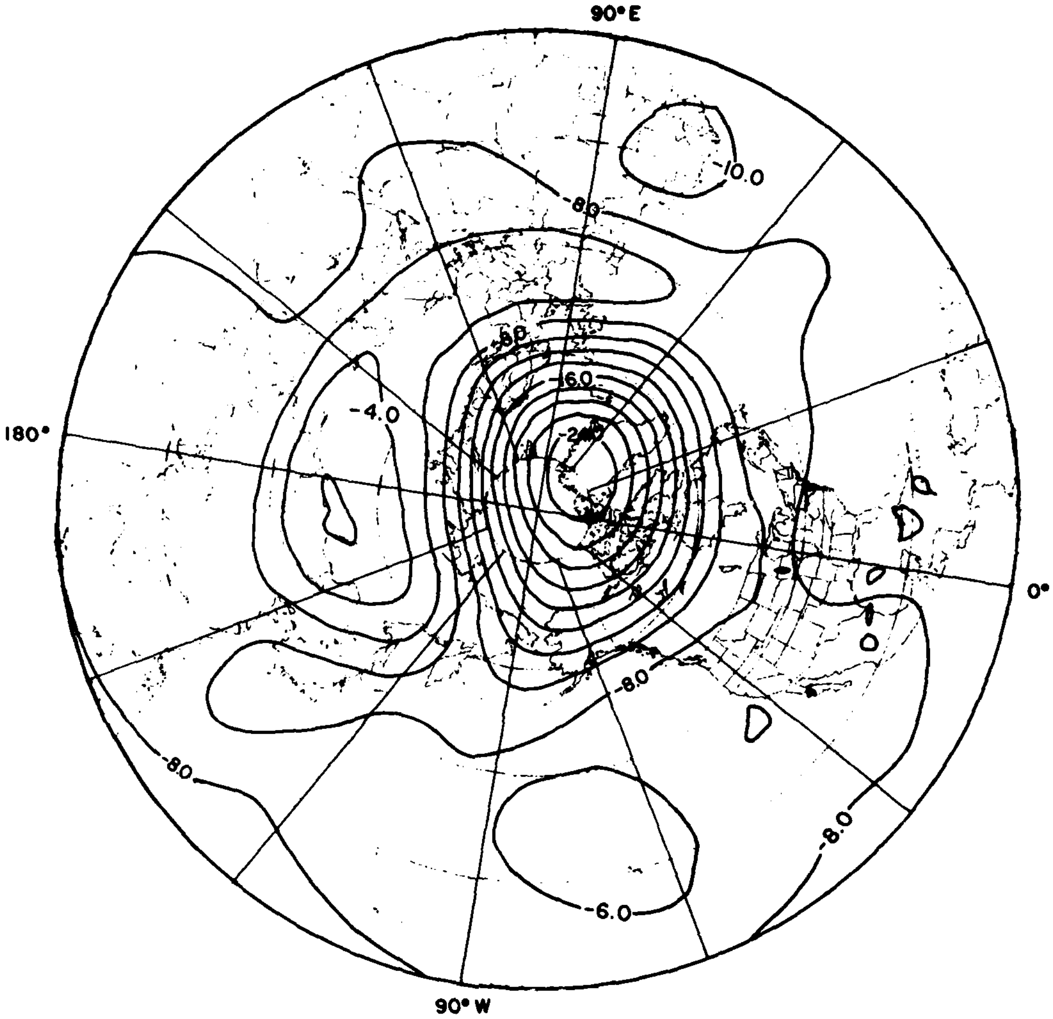


Figure A18. Density and rms Variability of Density at 55 km in the Fall



——— MEAN DENSITY AS PERCENT DEPARTURE FROM STD

Figure A19. Density at 30 km in the Winter

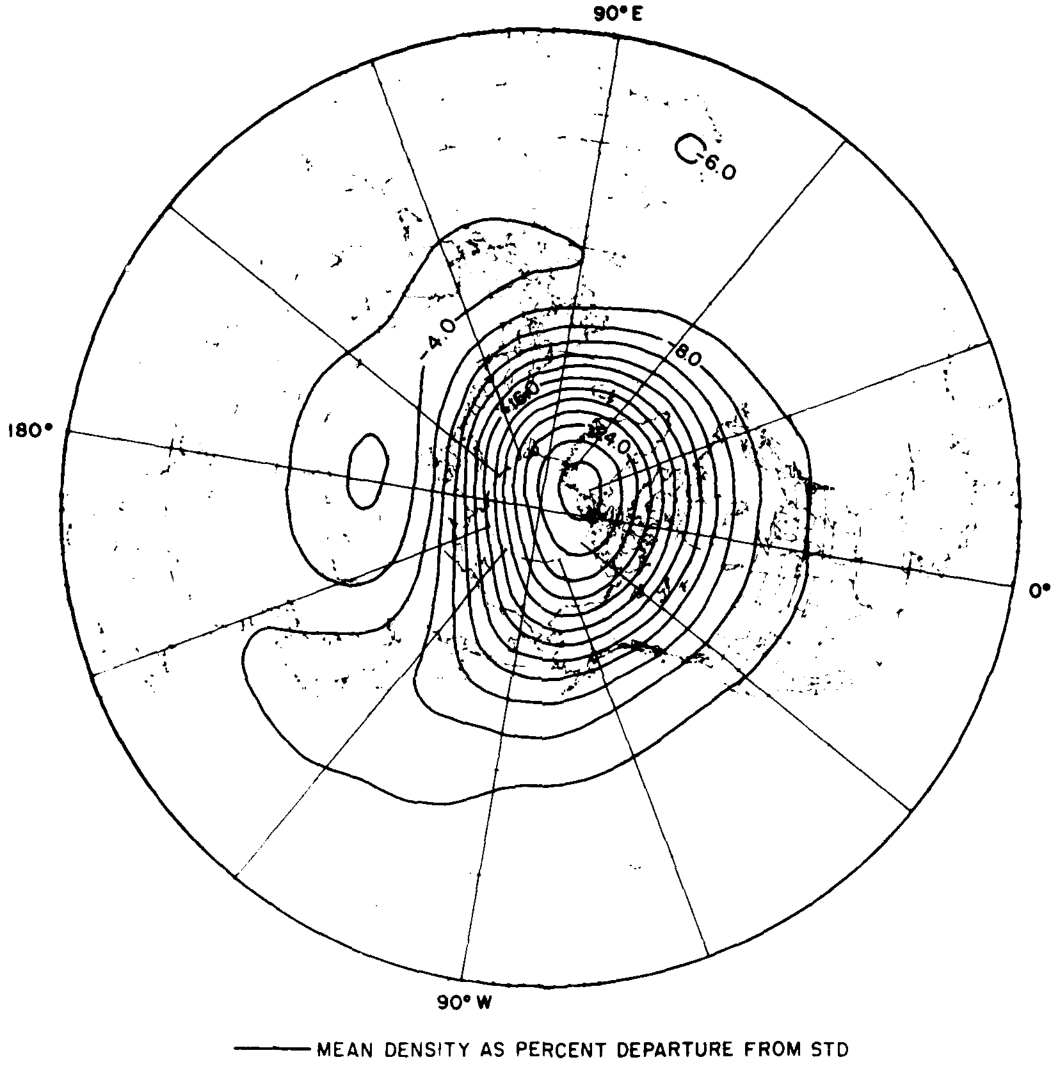
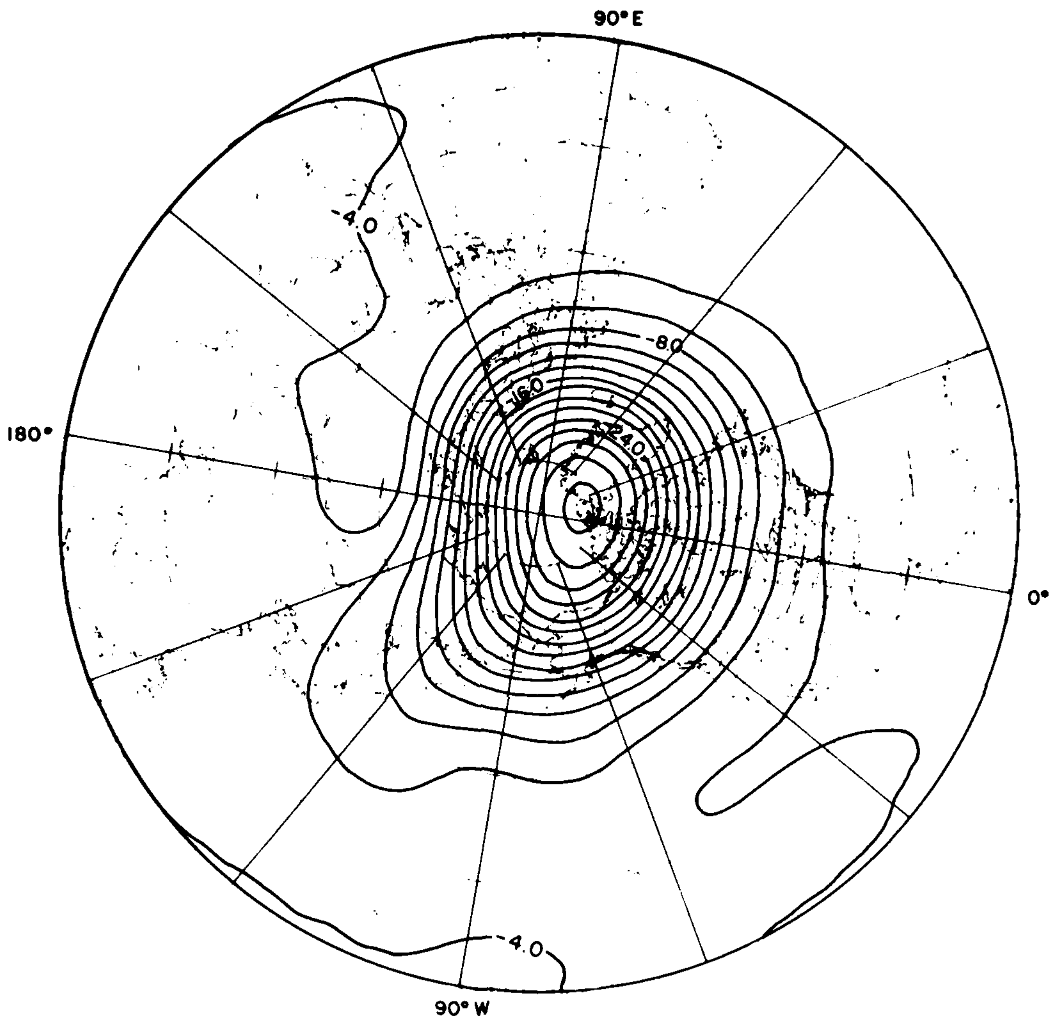


Figure A20. Density at 35 km in the Winter



——— MEAN DENSITY AS PERCENT DEPARTURE FROM STD

Figure A21. Density at 40 km in the Winter

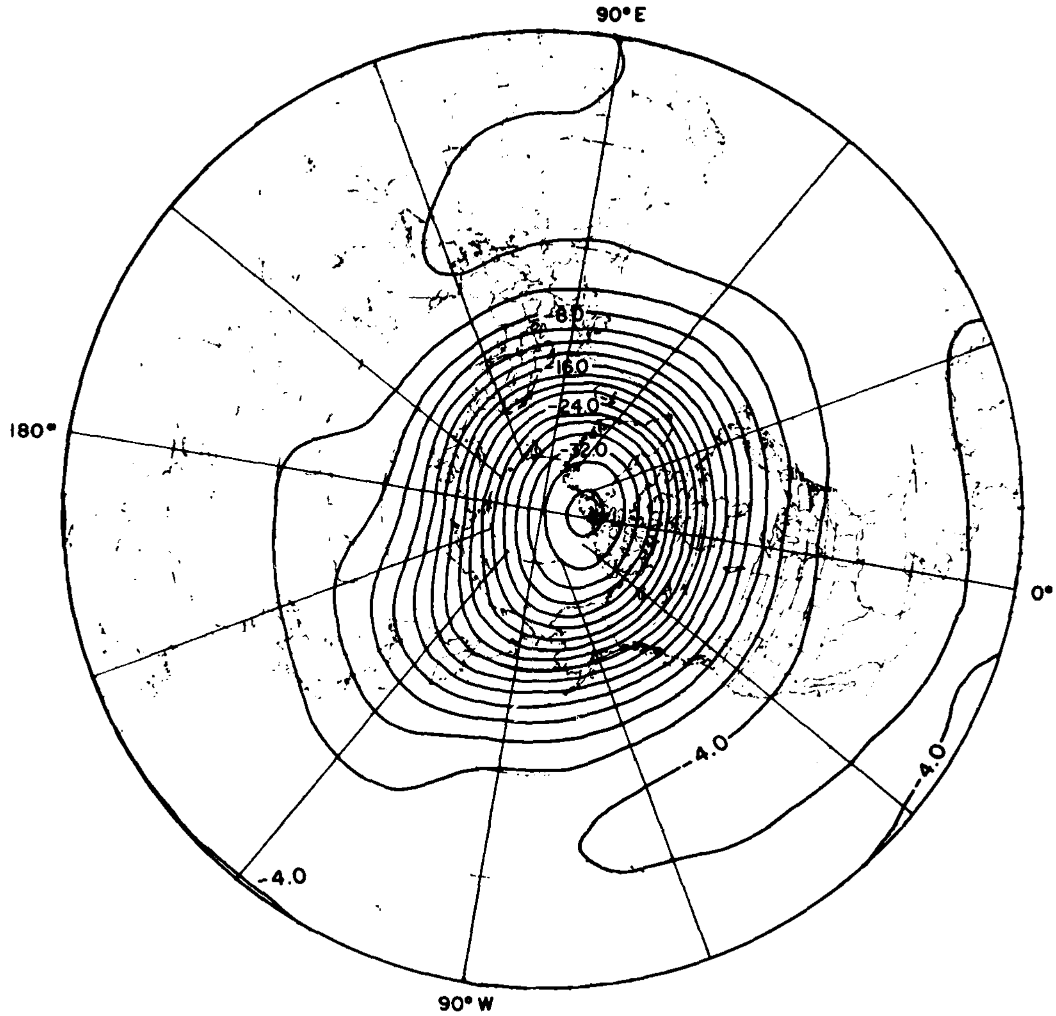


Figure A22. Density at 45 km in the Winter

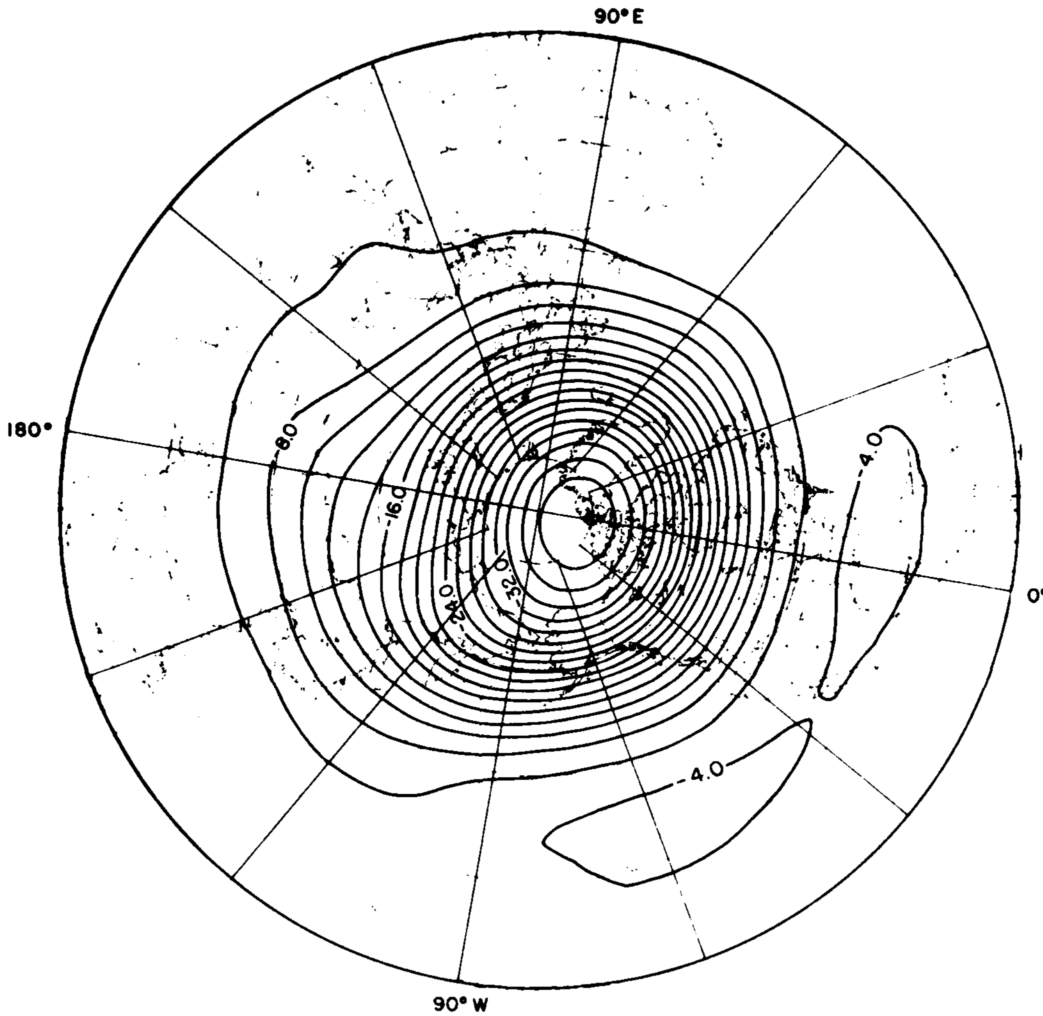


Figure A23. Density at 50 km in the Winter

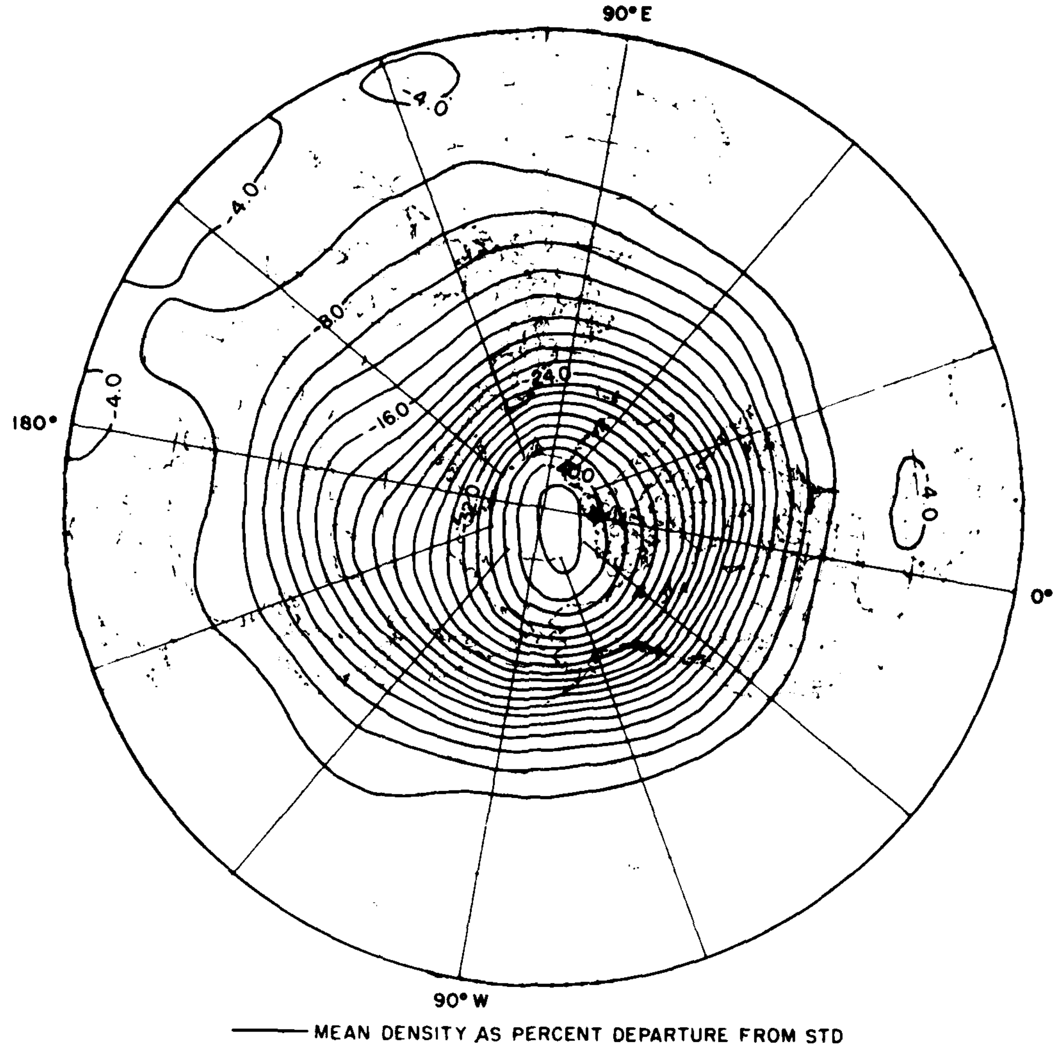


Figure A24. Density at 55 km in the Winter

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